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FUSION WELDING OF BERYLLIUM

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FOREWORD

This report was prepared by Bruce M. MacPherson and W. W. Beaver. The work carried out was under the direction of W. W. Beaver, Vice-President, Research and Development for The Brush Beryllium Company, Cleveland, Ohio, with operations supervised by B. M. MacPherson. This is the final report and describes the work performed from May 1, 1959, to August 31, 1960 under cost-sharing WADD Contract AF 33(616)-6413, Project No. 7351, "Metallic Materials", Task No. 73518, "Beryllium and Beryllium Alloys". The project is being administered by the Materials Central, Directorate of Advanced Systems Technology of the Wright Air Development Division, with Lt. S. S. Christopher as Project Engineer.

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I. INTRODUCTION

Applications for beryllium metal include inertial guidance instruments, air frames, space vehicle structures, and heat sink applications (including nose cones, re-entry vehicles and brake discs). Such applications will require high strength at temperature, freedom from re-entry angles (i.e., smooth surfaces), high modulus at the joint, and high thermal conductivity. In the light of recent welding developments it is felt that the major possibilities in these areas can be developed with the type of joint formed by a continuous butt weldment. Reliable joints with high thermal and mechanical properties found in fusion welded joints are needed.

The object of this work is to further develop the fusion welding process for joining beryllium, based on work previously performed by The Brush Beryllium Company. Fusion welding with or without filler wire has now been sufficiently developed so that the problems associated with obtaining crack-free joints appear to be solved for weldments under 1/4 inch thick. However, areas of possible improvement still remain. Welding techniques may be improved for welding thicker beryllium plates by the multiple pass process, mechanical properties nearer to those of the wrought beryllium metal being joined may be obtained and metal-inert gas welding of beryllium may be developed.

In this investigation, effects of residual impurities in beryllium were studied. Residual impurities in beryllium have been suspected by many investigators to be one cause of porosity and other detrimental effects during the fabrication of beryllium. The effects of residual impurities on beryllium are better understood from the results of physical and metallurgical evaluations of welds in the experiments performed under this program. These studies on the effects of residual impurities should help in explaining why weldability varies as the chemical composition of beryllium metal changes. Applying the residual impurity data should eventually aid in welding thick sections by multiple pass techniques and in improving the weld properties of fusion welds by the present welding techniques.

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II. BACKGROUND

The principal background for this work consisted of the joining development program carried out by The Brush Beryllium Company for the manufacture of inertial guidance systems, such as gyro control platforms and gimbals, which must be dimensionally stable under severe dynamic loadings. Initially, methods of soldering or brazing beryllium were considered for gyro components, but because dimensional stability is necessary, most of the soldered or brazed designs have been bypassed in favor of welded joints, preferably with beryllium metal added at the faying surfaces.

Nose-cone and re-entry vehicle applications which have also been considered, essentially require an integral joint of high thermal conductivity, preferably with a smooth surface without re-entry angles and without additive materials that create thermal unbalance. These requirements limit the materials that can be useful at the joint to primarily beryllium and silver (filler rods for fusion welding).

For structural applications, the same possibilities exist since high-temperature properties and a uniform metallurgical structure are required. The requirement has developed that beryllium be joined to high-temperature alloys (particularly to the austenitic stainless steel type).

Since beryllium has a strong tendency to oxidize at elevated temperatures, the tungsten-arc inert-gas welding process was chosen for fusion welding of beryllium. Initial studies were carried out with manual arc welding, using a standard butt-welding fixture with a copper backup having small holes about 1/4-inch apart, through which helium gas flowed directly onto the joint. These tests were unsuccessful. Further work was carried out in which the fixture containing the beryllium was preheated to 800° to 1000°F.

In experiments on beryllium sheet from 0.040 to 0.110-inch thick under conditions of improved temperature control, boxes with square corners of different gauge sheets were welded successfully. Thus it appeared that the high thermal conductivity of beryllium was a major problem, and that control of heat flow out of the weld zone was necessary for successful welding.

Cracks forming in and around the weldment were largely caused by thermal shock. Sound welds in beryllium were obtained by providing insulation around the parts to be welded. Asbestos cloth and aluminum oxide were used successfully as insulators around the welding area to provide uniform heat retention in the weldment. For precision automatic

welding, the backup bar and clamping fingers, which were made of austenitic stainless steel, were coated with thermal insulating materials. By thermal insulating the weld area, the welding heat is retained in the area of the weld which has the effect of preheating although this is not normally considered preheating. External preheating could be advantageous where insufficient heat is produced by the welding arc to maintain thermal equilibrium in the weld area such as in the welding of thick beryllium sections.

Single-pass "V" fillet welds made on beryllium plate 1/4-inch thick or thicker have a tendency to check-crack as do heavy weldments in stainless steels. This is most likely due to the larger weld grain size caused by the longer time the weld metal is molten. Multiple pass welding, if possible with beryllium, could be a solution to this problem. The use of high-oxide beryllium filler rod might help also. The most promising technique for heavy beryllium plate weldments appears to be in the use of silver alloy filler rods. However, insufficient art has been developed on silver alloy rods in comparison with that developed on the use of beryllium metal filler rods.

Inert atmospheres have been obtained by surrounding the entire operation with a large plastic tent in which argon and helium were contained (Figure 1). This expedient proved to be a very successful way to operate, since the tent is cheap, very flexible, and can be provided in large sizes with a zipper to permit the entry of large welded structures. The flexibility of the plastic bag is such that the operator can move his arms freely. The tent itself is inflated by the internal gas pressure of the inert atmosphere.

By use of the inert-arc welding process, fusion welds of 90-degree angle joints could be accomplished in sheet up to 0.125-inch thick; and with slightly more difficulty 180-degree butt welds could be accomplished. The problem of control of grain size increases with thicker sheets. Essentially, very fine grained weld beads were obtained in 0.060-inch sheet, whereas the grain size approached 100 microns in 0.125-inch sheet. The tensile strength and ductility were also a function of grain size, reaching a maximum of 37,500 psi in 1.6% elongation in 0.060-inch sheet. Generally, welds of satisfactory appearance varied in strength from 25,000 to 37,500 psi and elongations varied from 0.4 to 1.6%, provided that the average grain size of weld did not exceed 100 microns. The grain size obtained in the weld microstructure has varied, usually between 60 and 120 microns. Sheet butt-welded together could be hot and warm rolled to thinner foil, with the weld becoming indistinguishable from the parent metal. This indicated that welds of the grain size developed can be worked without cracking. After rolling, the tensile strength of the weldments increased, nearer to that of the original base metal.

Fig. 1 - Arc Welding in an Inert-Atmosphere Plastic Tent

Welding of thicker sheet by inert-arc methods, using a tungsten electrode or essentially a no-filler-rod method, did not provide sufficient weldment to fill the joint, resulting in depressions at the bead. Therefore, beryllium weld rods were used to provide sufficient metal for the fill. Despite previous comments in the literature that in fusion welding with beryllium rod, the filler metal would not flow and would not even lay down, these operations were performed successfully under the conditions discussed. In fact, it was possible to penetrate a sheet with no cracks appearing on the bead or surrounding metal by merely laying down weld metal in the center of the sheet. Consequently, it appeared that the filler rod method, rather than simply melting the surfaces together, could be used with considerable advantage in the thin sheet, providing better control of the fill and the reinforcement. The filler rod method appeared to be necessary for joining thicker sheet.

In an effort to find better welding conditions for the welding of beryllium, many variables were exploited. When variations of the settings recommended in the literature of direct-current with direct polarity were used, very poor results were obtained. With direct current and reverse polarity, no weld could be made. The best results were obtained when alternating current and high-frequency arc starting were used. Various arc atmospheres were tried. With the flow rate varied according to material thickness, a 50-50 mixture of argon and helium as an arc atmosphere has been found to be best for welding, producing the cleanest welds.

The arc welding process developed by The Brush Beryllium Company has been applied successfully to a number of fabricated shapes. In Figure 2 is a welded gimbal assembly for a large inertial guidance unit. The gimbal was assembled by welding hot-rolled plate to a hot-pressed machined support section with beryllium filler rods. The support section was about 0.100-inch thick to which 0.080-inch hot-rolled sheets were attached. Machining damage in the base structure was also repaired by welding with a beryllium filler rod. In Figure 3, a structure is shown which was welded by joining a roll-formed sheet into a ring, at the same time penetrating into another internal section so that the surface of one sheet and the edge of two were welded simultaneously. Figures 4 and 5 show a welded cone and welded cylinders both before and after removal of the weld reinforcement. Figure 6 shows a 1-inch-diameter 0.019-inch-wall tube which was automatically welded without filler material. This tube was helium leak tested and had a vacuum leak rate which was better than 5×10^{-7} cc/sec of mercury.

The inert-arc welding process developed for beryllium was compared with the ion-beam method, as satisfactory weldments made by the latter method have been received from several installations. In general, the

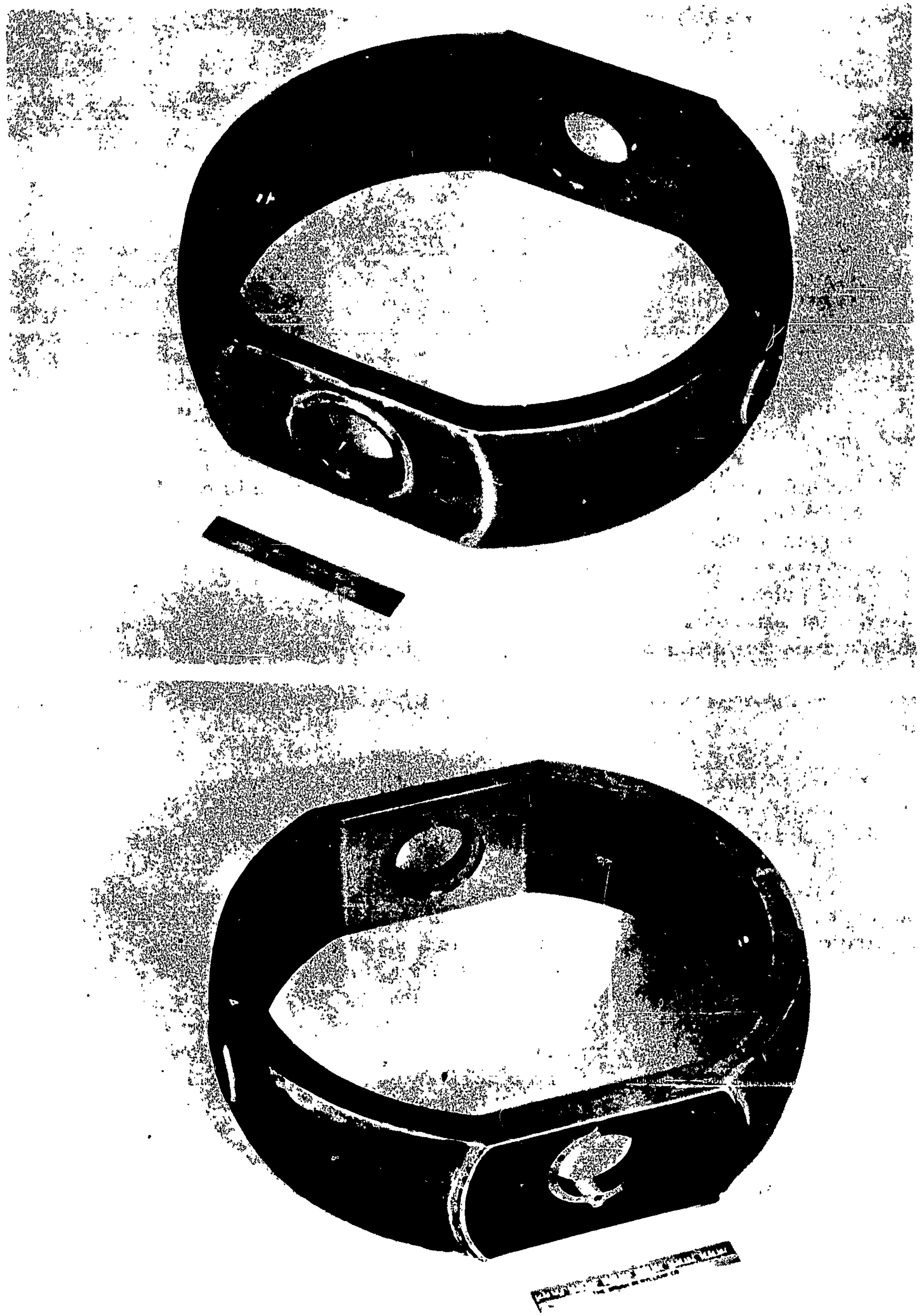


Fig. 2 - Welding Gimbal Assembly

Fig. 3 - Roll Formed 9 1/8-Inch Diameter Welded Ring of 1/8-Inch Beryllium Sheet with 1/8-Inch Beryllium Sheet Backup

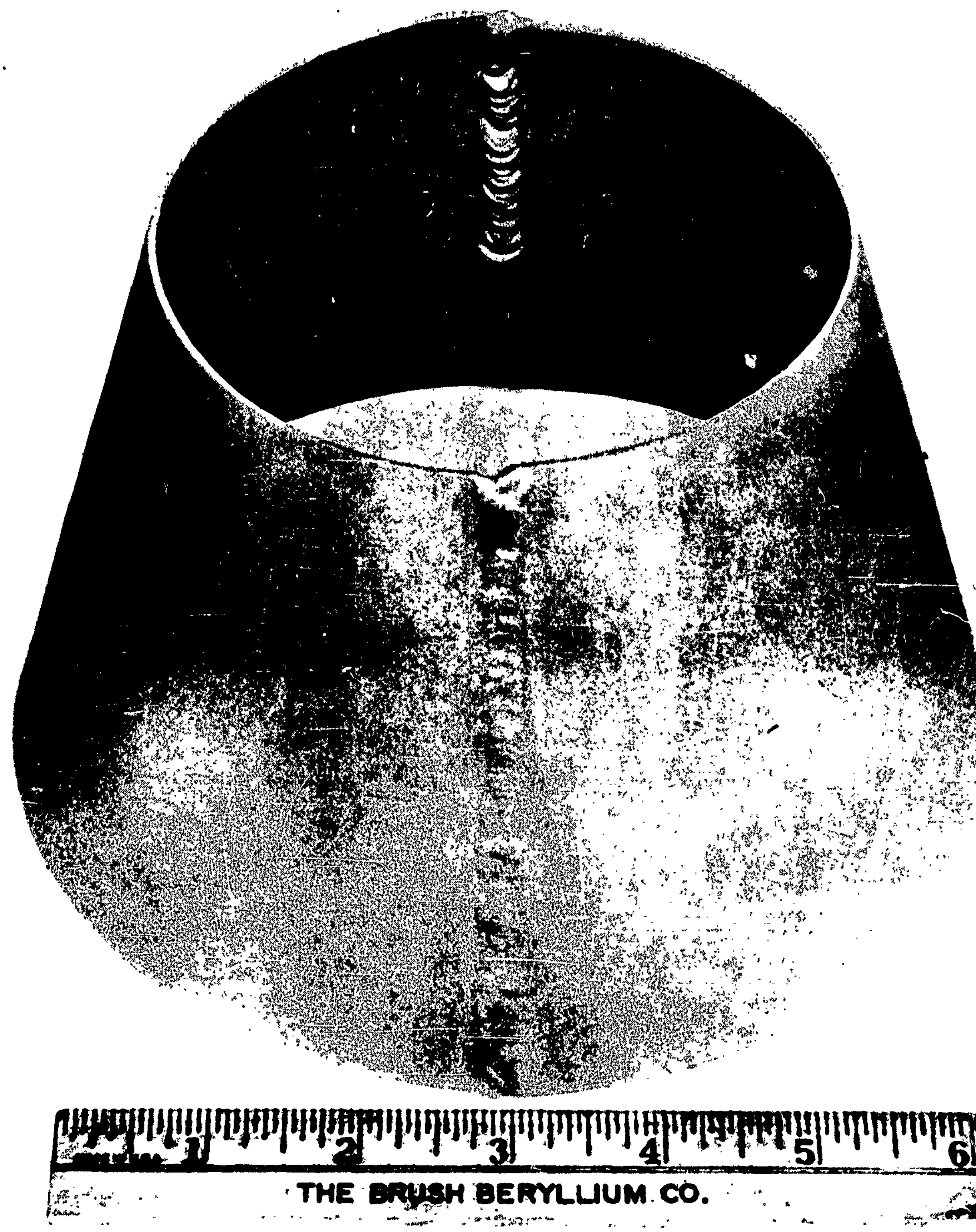


Fig. 4 - Truncated Cone Made by Roll Forming and Welding with Beryllium Filler Rods

Fig. 5 - 0.130-Inch-Thick Beryllium Sheets Roll Formed and Welded (Using Beryllium Filler Rods) into 7-Inch-Diameter Tubes

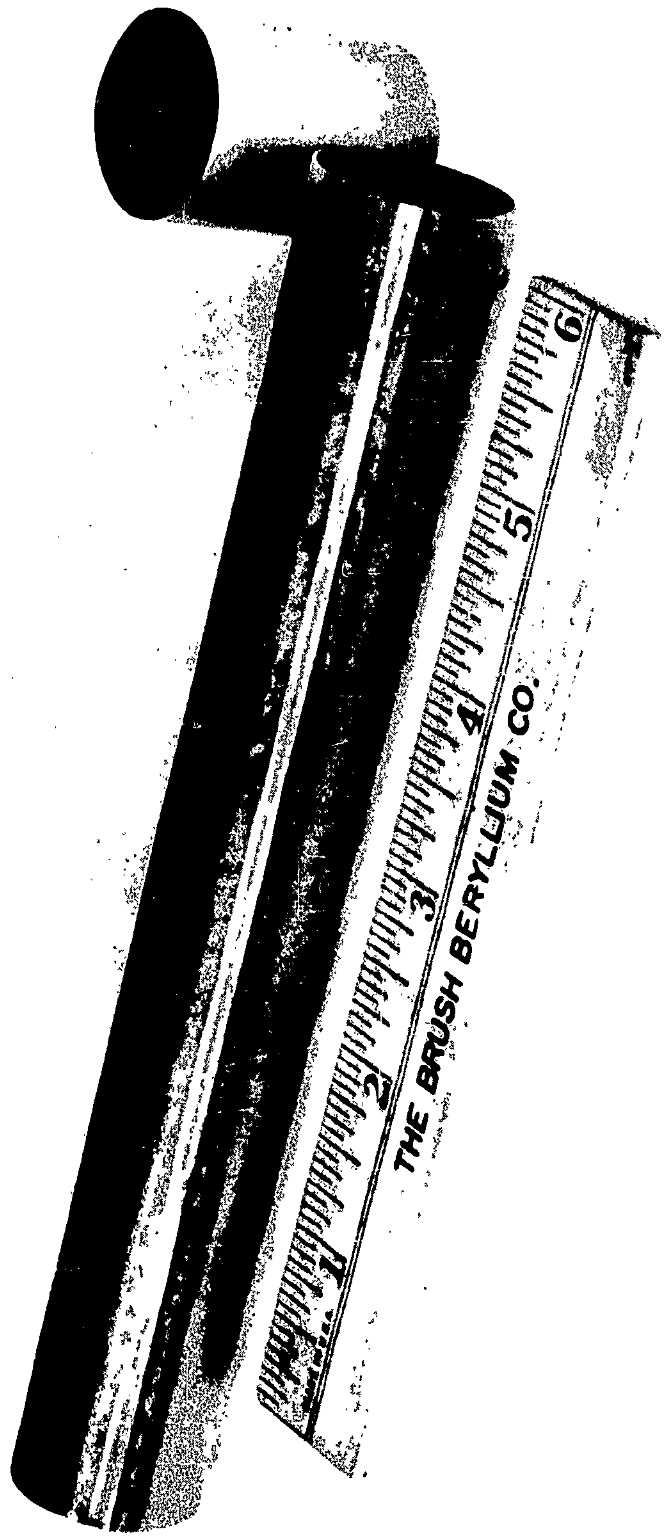


Fig. 6 - 1-Inch-Diameter, 0.019-Inch-Wall Tubing Automatically Welded Without Filler Rod

properties and structure obtained by the inert-arc and ion-beam methods were identical. Since high-vacuum conditions are necessary for the ion-beam welding method, the inert-arc method should be much cheaper when applied to general structural welding operations for air and space vehicles.

One problem in the welding of beryllium by inert-arc welding methods is that of small pores showing up in the bead when certain welding rods are used. This necessitated an investigation into control of the welding-rod material used. Another problem is grain growth obtained in weld areas, although this is not always detrimental in relation to mechanical properties.

In Figure 7, the properties of QMV hot-pressed beryllium are compared with those those of beryllium weld filler metal, showing that at higher temperatures, the coarser grain weld metal has better tensile properties and, over the entire temperature range, more uniform tensile properties. Consequently, the problem of obtaining satisfactory weld properties is not entirely one of developing fine grain size.

As part of arc welding development, some work has been done using filler materials of metals other than beryllium. Aluminum-silicon alloys and beryllium-silicon alloys showed either a very brittle structure (Be-Si) or a poor tensile strength (Al-Si). The best results obtained in welding beryllium to beryllium (other than by the use of beryllium metal filler) were by the use of a silver filler wire.

In brazing research at The Brush Beryllium Company, it has been determined that the presence of small amounts of lithium and phosphorus in silver, copper, and nickel will substantially reduce diffusion and consequent formation of brittle phases, including intermetallics. These alloys have been used extensively in brazing and welding operations. In the case of the silver alloy, strength at room temperature was raised to the highest yet achieved by arc welded material, essentially 41,000 psi, at room temperature. Generally it is preferable to use beryllium rods for welding beryllium to beryllium, but in the case of high-temperature materials or joints in thick plate, including the welding of high-oxide beryllium and beryllium to stainless steel joints, the use of silver alloy rods may be considered.

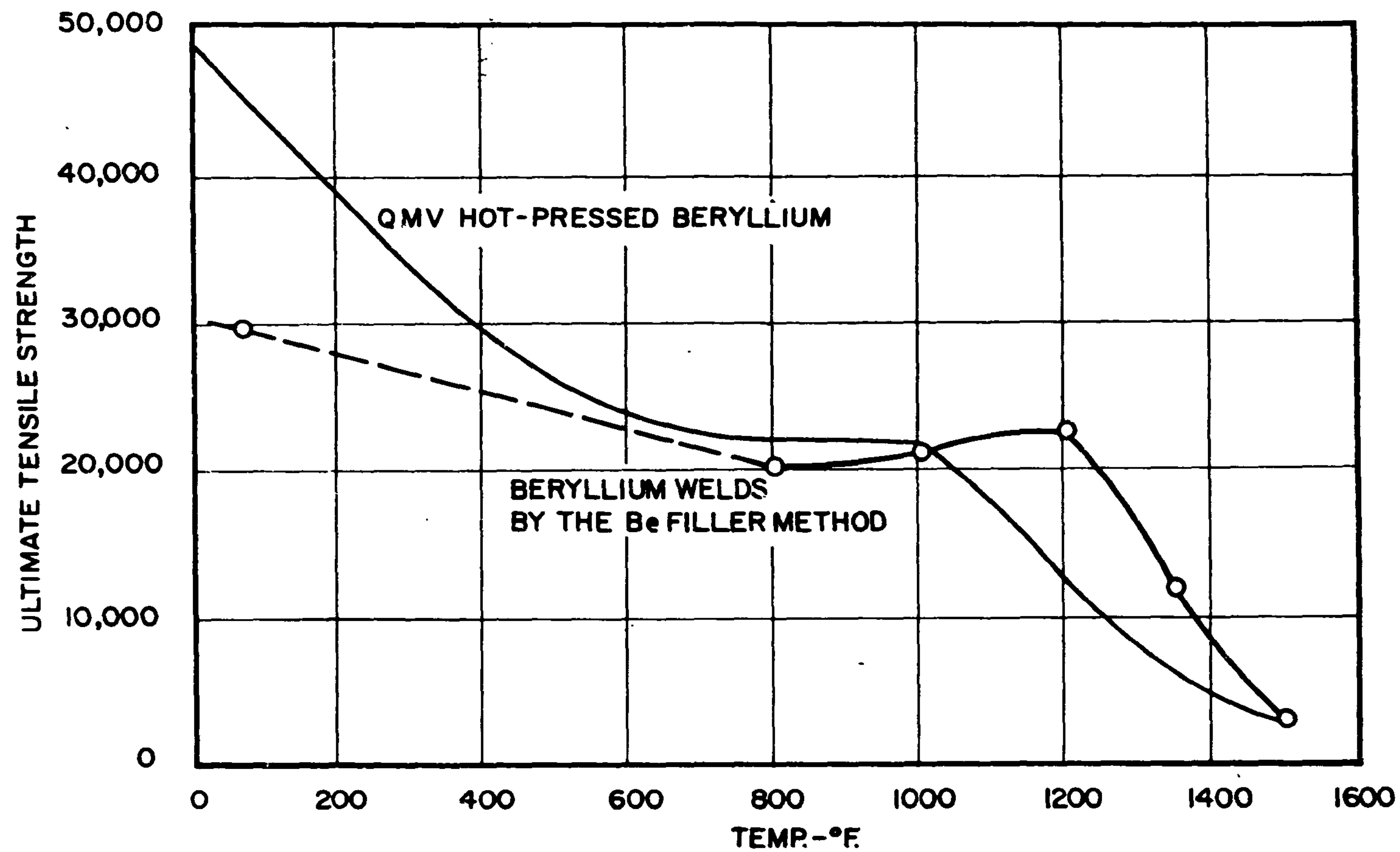


Fig. 7 - Comparison of QMV Hot-Pressed Beryllium with Beryllium Welds by the Beryllium Filler Method. Strengths at Room Temperature Vary from 29,000 to 37,500 psi According To Grain Size

III. EXPERIMENTAL WORK AND RESULTS

A. Weldability of Beryllium

1. Standard Welding Conditions

Although many of the basic principles of fusion welding of beryllium had been established prior to this program, full standardization of all interrelated conditions had not been fully explored; therefore, initial metallurgical studies were required to develop a standard welding condition in order to guide other welding experiments. The welds used for this first phase were made on 1/8-inch QMV virgin beryllium sheets, with drawn beryllium wire generally used as filler.

For an oxide-free surface, all beryllium metal used in this program was cleaned by pickling in a nitric-hydrofluoric acid bath prior to the welding operation. This cleaning operation consisted of dipping the beryllium parts into a 40% HNO_3 - 2% HF -58% H_2O solution for approximately two minutes at room temperature; this pickling time can vary considerably according to the size of the parts to be pickled and the strength of the pickling bath.

Using a consistent setup (high-frequency and alternating current with a 50-50 mixture of argon and helium as an arc atmosphere), the welding amperage was varied to determine the optimum welding current requirements for various thicknesses of beryllium. The maximum welding currents that would yield satisfactory welds for 1/8-inch-thick beryllium and for thicknesses above and below 1/8 inch were determined. These data, which are given in Figure 8, are applicable for an approximate range of 0.050- to 0.250-inch thickness. Less amperage is required for beryllium thicknesses below 0.050-inch than would be predicted by extrapolation of this curve.

If more current is used for a given thickness than that prescribed in Figure 8, the resultant weld will tend to have increasingly larger grain and in addition weld cracking and porosity are likely. In Table I are given the welding conditions for weldments shown in Figures 9 to 14.

The major welding condition which varied in the welds shown in the photomicrographs of Figures 9 through 12 was the welding amperage used. The weld in Figure 10 was made with 20 to 25% more amperage than that shown in Figure 9, and the average cross-sectional grain size is about 50% greater in Figure 10 than in Figure 9. Figure 11 shows the top and side sections of the same weld that is shown in Figure 10 cross sectioned.

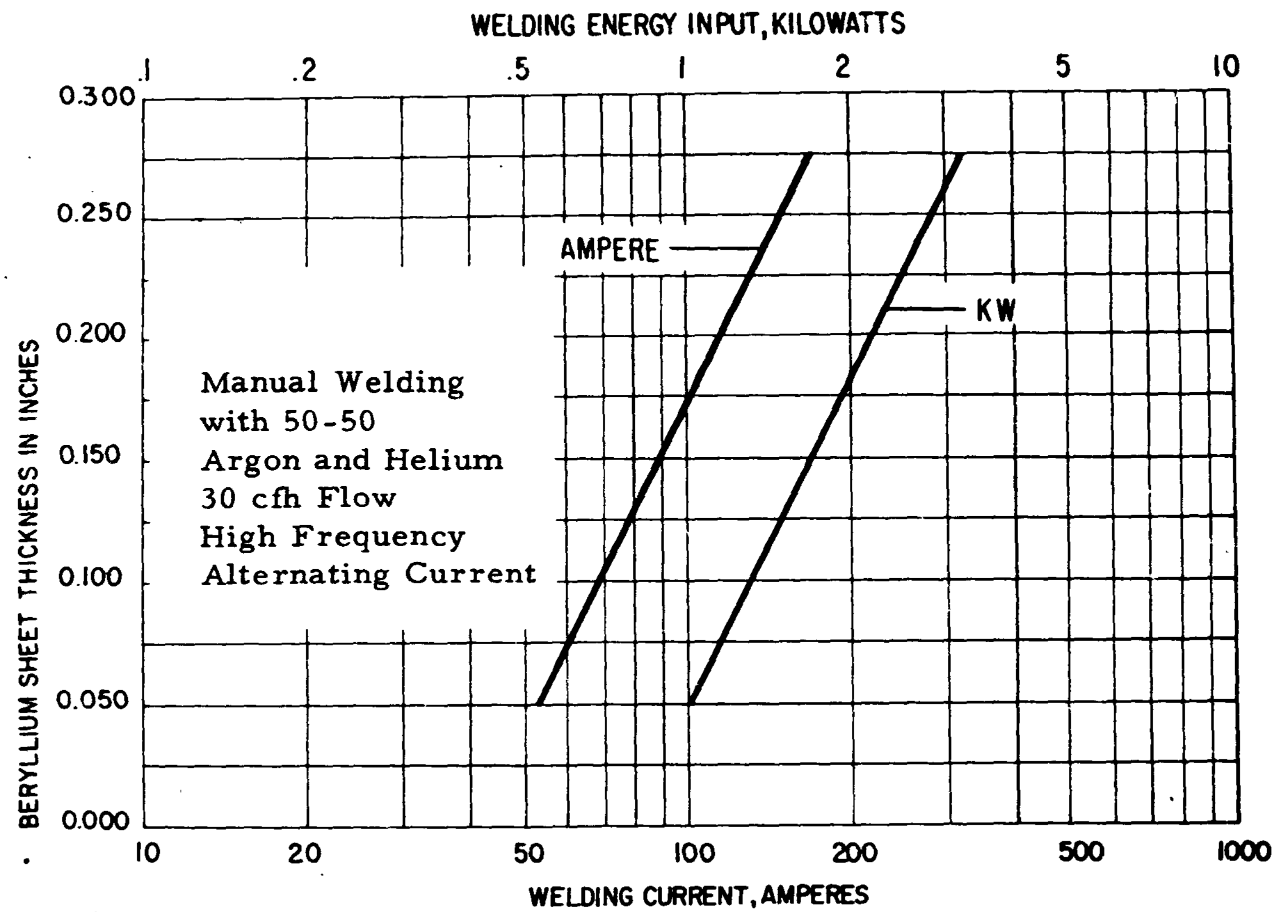


Fig. 8 - Maximum Welding Current for Inert-Arc Welding of Beryllium

TABLE I

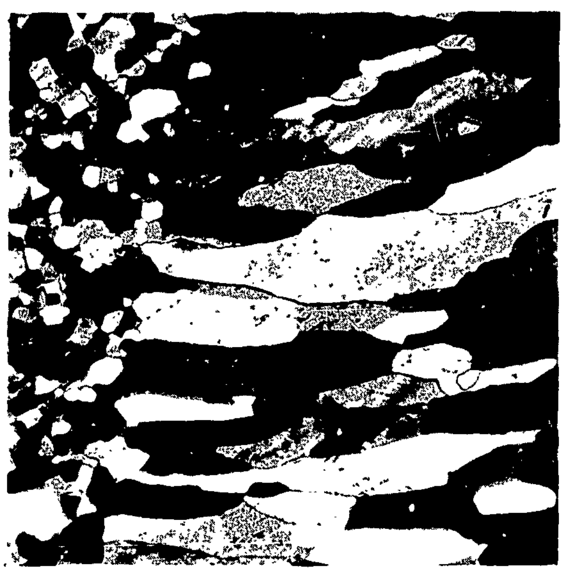
PLATE THICKNESS, WELDING AMPERAGE, AND AVERAGE GRAIN SIZE OF BERYLLIUM WELDMENTS

	Plate Thickness (in.)	Welding Amperage (amp)	Average Weld Grain Size (μ) Center of Weld	Parent Metal
Figure 9, A and B	1/8	60-65	65	25
Figure 10, A and B	1/8	75-78	100	25
Figure 11, A and B	1/8	75-78	85	25
Figure 11, C	1/8	75-78	95	--
Figure 12, A	1/8	110	90	--
Figure 12, B	1/8	110	100	--
Figure 12, C and D	1/8	110	90	35
Figure 13, A and B	1/8	--	120	24
Figure 13, C and D	1/8	--	80	27
Figure 14, A and B	1/4	155	100	18

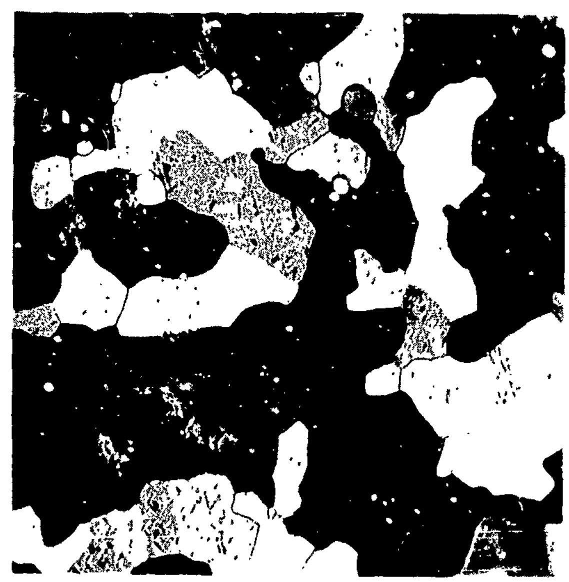
A. Cent-- of Weld

B. Parent Metal and Weld

Fig. 9 - Cross Section of 1/8-Inch-Beryllium Plate Fusion Welded Using 60-65 Amperes, 100X

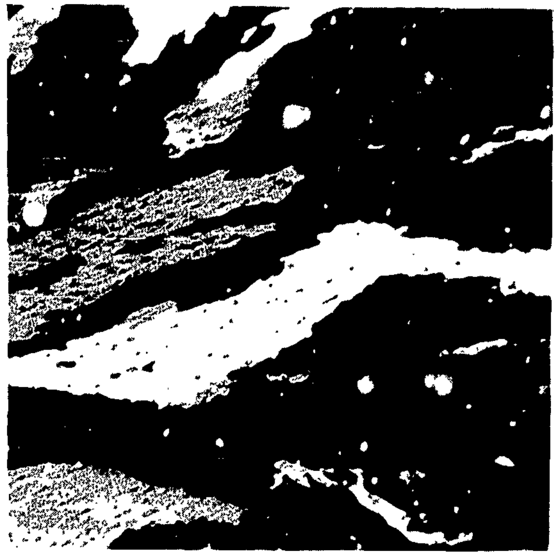


A. Center of Weld



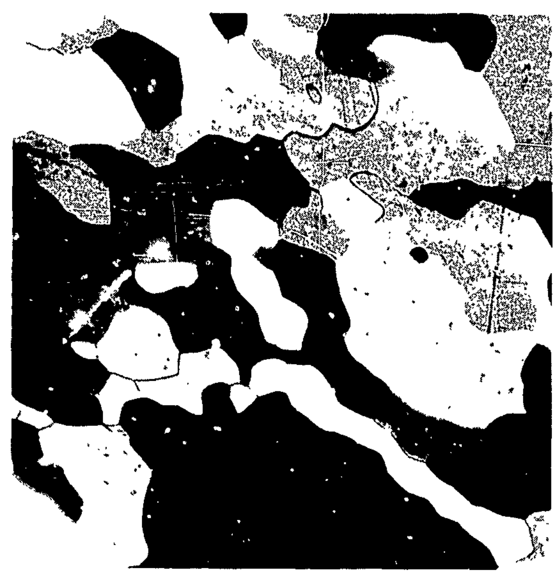
B. Parent Metal and Weld

Fig. 10 - Cross Section of 1/8-Inch Beryllium Plate Fusion Welded Using 75-78 Amperes, 100X



A. Center of Weld
(Top View)

B. Parent Metal and Weld
(Top View)



C. Center of Weld
(Side View)

Fig. 11 - Top Views and Side View of the Same Weld as is Shown in Figure 10, 100X

A. Center of Weld
(Top View)

B. Center of Weld
(Side View)

C. Center of Weld
(Top View)

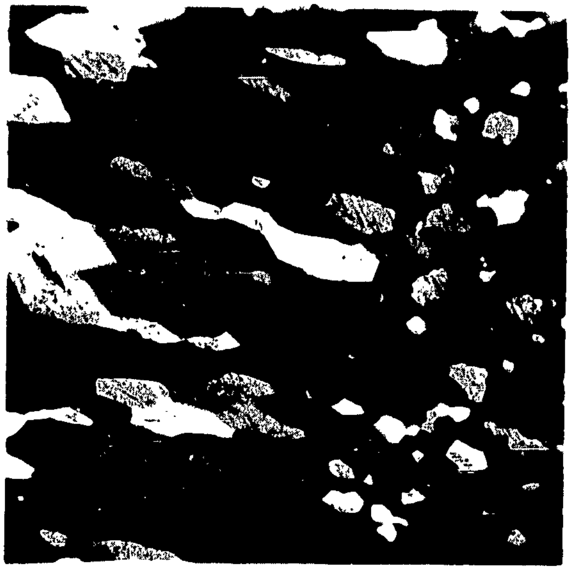
D. Parent Metal and Weld
(Top View)

Fig. 12 - Top Views and Side of 1/8-Inch Beryllium Plate Fusion Welded Using 110 Amperes, 100X

A. Center of Weld

B. Parent Metal and Weld

C. Center of Weld



D. Parent Metal and Weld

Fig. 13 - Cross Section of 1/8-Inch Beryllium Plate Fusion Welded Using Drawn Beryllium Wire, A and B, 1/2 Inch from Beginning of Weld, and C and D, 7 1/2 Inches from Beginning, 100X

A. Center of Weld

B. Parent Metal and Weld

Fig. 14 - Cross Section of 1/4-Inch Beryllium Plate Fusion Welded Using Beryllium Filler Rod, 100X

Unlike the welds made with lower amperage, the welds shown in Figure 12 have cracks, larger grains, inclusions, and porosity, as is shown in photomicrographs A, B, C, and D. These detrimental effects were caused by using an amperage setting slightly too high for the 0.125-inch thickness (see Figure 8).

The metallographic examination of the initial manual welds made with filler wire indicated that the grain size at the beginning of the welds was considerably larger than the grain size in the rest of the weld. It was theorized at the time that this larger grain size was due to the fact that no preheat was employed in the welding operation. In this manual welding operation, the weldor welds more slowly at the beginning of the weld, until he approaches a heat equilibrium. The larger grain size at the beginning of the weld can be seen in Figure 13. The weld cross section shown in photomicrographs A and B were taken 1/2 inch from the beginning of the weld, and the weld cross section shown in metallographs C and D were taken 7 1/2 inches from the beginning of the weld. Further testing has shown that this effect can be greatly reduced by having a lead-on welding strip of beryllium at the beginning of the weld; thereby welding equilibrium can be approached before the actual welding begins.

In an effort to better understand the heat flow pattern in the beryllium fusion welding operations, a thermocouple was placed under the beryllium sheet one-quarter inch away from the weld at a point three inches from the beginning of the weld. (This again was done using the manual TIG process on 1/8 inch thick S-200-B grade beryllium sheet.) The temperature three inches from the beginning of the weld was recorded in relation to time, starting when the welding commenced. Thermocouple readings taken on four different weldments at this location were plotted (Figure 15). Tests No. 2 and 5 were welded with the beryllium sheets at room temperature prior to striking the arc. In Test Nos. 4 and 6, the beryllium sheets were approximately 25° and 50°C, respectively, above room temperature just prior to striking the arc. (The thermocouples broke during tests 1 and 3.) Figure 15 indicates that the conditions for the fusion welding of beryllium are critical to the control of the heat equilibrium of the weld zone, and the proper control of the heat equilibrium is necessary for maintaining a uniform fine grain structure. From examination of these curves, one can note that our welding operation is slow - near approximately one inch per minute.

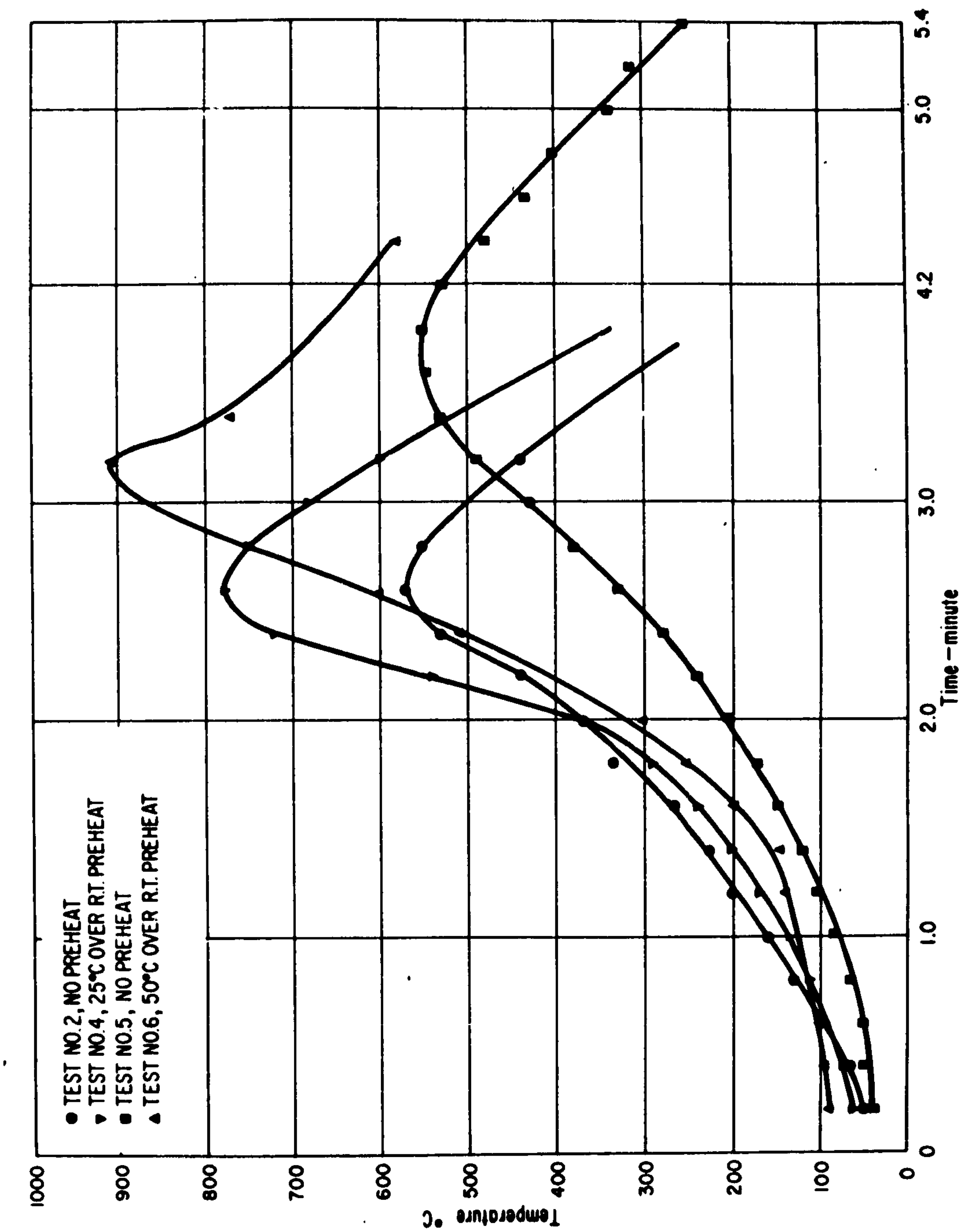


Fig. 15 - Thermocouple Readings Taken from Beginning of Weld

Photomicrographs shown in Figure 14 are of a weld made on 1/4-inch-thick QMV beryllium sheets. This work on 1/4-inch-thick beryllium sheets was important in the study of maintaining good heating equilibrium, since the heat equilibrium problem increases with thickness. All welds made for this program on 1/4-inch-thick beryllium sheets were crack-free and sound.

Tensile results for these welds and for the welds made in 1/8-inch virgin beryllium sheet are reported in Table II. Sound welds that have been made on 1/8-inch and 1/4-inch thick S-100 series sheet and 1/4-inch thick S-200 series sheet were subjected to tensile testing at controlled temperatures (room temperature, 600°, 800°, 1200°, -110°, and -167°F). Although the welds made on 1/8-inch S-200 series sheets had stringer porosity at the edge of the welds and also a limited amount of porosity on the surface of the welds, these welds were also tested under the above conditions (Table II.)

Surface porosity is usually eliminated by close control of the welding parameters; however, stringer porosity is retained in the weld in most cases. Stringer porosity, which shows up under X-ray radiography at the edge of the weld, appears to be coming out of the parent metal. It is most likely caused by vaporization of some constituent of the parent metal, even though chemical analysis of the base metal indicates no unusual impurities. The stringer porosity which appears when welding some heats of beryllium is apparently greater when welding transversely to the direction of rolling than when welding longitudinally to the direction of rolling.

2. Post-Heat Treatment of Beryllium Welds

Although a post-heat treatment of 825°C for thirty minutes has been used for many years on all beryllium fusion welds, there has never been a study to determine the best temperature and time for this post-heat treatment. In the original studies several years ago, as much as 9,000 psi increase in tensile strength was attained by use of this standard post-heat treatment, as compared to tensiles in the as-welded condition. In the more recent tests as shown in Tables III and IV, it appears that the basic strength in the as-welded condition has increased sufficiently so that the increase effected by post-heat treatment is not

TABLE II

MECHANICAL PROPERTIES OF BERYLLIUM FUSION WELDS

Test Temp. (°F)	Ult. Str. (psi x 10^3)	Yld. Str. (psi x 10^3)	Modulus (psi x 10^6)	Cont. (%)	Elongation in 1/8 in. (%)	Elongation in 1/4 in. (%)	Elongation in 2 in. (%)
			1/8-inch S-100 Series Beryllium*				
R. T.	32.0	-	43.4	3.2	5.6	3.2	0.4
	26.7	-	39.5	0.0	5.6	3.6	0.4
600	23.8	20.9	36.2	0.9	3.5	2.0	0.3
	28.6	23.6	36.6	2.3	8.3	6.5	1.8
800	18.7	13.4	-	5.7	12.3	8.7	2.5
	16.9	-	-	0.8	2.3	1.2	0.15
1200	17.4	13.2	-	9.5	15.4	12.5	4.0
	19.5	17.5	-	5.2	17.3	12.5	2.0
-67	28.6	-	-	0	3.5	1.8	0.2
-110	31.0	-	45.8	0.2	1.5	0.8	0.1
	27.6	-	39.8	0.2	3.1	1.6	0.2
			1/4-inch S-100 Series Beryllium*				
R. T.	28.0	-	40.3	0.1	--	--	--
	27.2	-	-	0.2	--	--	--
600	24.9	20.0	42.3	7.2	15.8	12.0	2.0
	24.0	18.0	-	4.6	11.1	8.7	2.0
800	22.2	16.6	-	23.5	64.1	52.8	9.3
	22.5	15.4	-	21.8	47.3	46.2	8.8
1200	14.6	10.0	-	3.5	8.1	7.4	1.0
	16.0	11.5	28.2	9.8	9.5	9.5	1.2
-67	30.1	-	38.2	0.2	3.6	2.4	0.4
-110	23.4	-	-	0	1.1	0.6	0.1

(Continued)

TABLE II (Continued)

MECHANICAL PROPERTIES OF BERYLLIUM FUSION WELDS

Test Temp. (%)	Ult. Str. (psi x 10^3)	Yld. Str. (psi x 10^3)	Modulus (psi x 10^6)	Cont. (%)	Elongation in 1/8 in. (%)	1/4 in. (%)	2 in. (%)
			1/8-inch S-200 Series Beryllium*				
R. T.	22.0	-	41.1	1.0	3.2	2.8	0.1
	20.5	-	40.8	0.0	7.9	3.2	0.2
600	19.8	-	-	0.3	8.2	5.1	0.8
	19.7	18.9	-	2.3	14.3	7.0	0.8
800	23.0	18.9	-	17.8	29.2	22.3	3.3
	20.6	14.1	-	16.8	28.9	27.4	4.0
1200	17.5	12.1	-	5.4	15.4	10.2	1.3
	16.3	14.4	-	14.3	34.6	22.5	3.4
-67	32.3	-	-	0	5.4	2.7	0.4
	29.4	-	44.5	0	0.8	0.4	0.05
-110	25.5	-	48.8	0	2.3	1.2	0.2
			1/4-inch S-200 Series Beryllium*				
R. T.	31.9	-	38.8	0.6	1.6	0.8	0.1
600	25.0	17.7	-	7.5	20.2	15.8	2.5
	24.8	21.3	45.0	5.0	16.5	10.9	2.0
800	22.0	13.5	-	26.5	56.3	44.5	7.1
	20.2	-	-	11.8	21.5	17.3	3.5
1200	13.1	10.3	22.3	1.9	23.1	17.6	3.5
	15.5	12.5	-	11.4	20.2	20.2	2.9
-67	25.0	-	-	0.5	6.5	3.3	0.4
	23.2	-	-	0	3.1	1.5	0.2
-110	29.2	-	38.1	1.2	1.2	0.2	0.2
	22.7	-	-	0.5	4.6	3.0	0.4

*S-200 is a commercial Brush Beryllium Company specification.

TABLE III

EFFECTS OF POST-HEAT TREATMENT ON BERYLLIUM FUSION WELDS

Post-Heat Treatment	Average Tensile Strength	Average Elongation in 2 inches (%)
None	25,500	0.3
780°C-30 min	26,900	0.5
780°C-1 hour	26,800	0.4
780°C-2 hours	26,300	0.4
780°C-4 hours	26,800	0.4
825°C-30 min	28,200	0.4

TABLE IV

POST HEAT TREATMENT STUDIES OF FUSION WELDS - TRANSVERSE WELDS

Post Heat Treatment	Ult. Strength (psi)	Elongation in 2 inches (%)	Elongation in 1/4 inch (%)	Elongation in 1/8 inch (%)	Cont. (%)	Mod. of Elasticity (psi x 10^6)
As Welded	32,600	0.2	1.6	3.2	0.4	51.8
As Welded	29,400	0.0	0.0	0.0	2.1	43.7
As Welded	30,400	0.0	--	--	0.5	
825°C	30,700	0.3	2.0	4.0	0.5	47.1
825°C	30,300*	0.3	2.1	3.2	6.5	47.6
825°C	30,700	0.2	1.6	3.2	1.1	43.4
825°C	32,300	0.0	--	--	0.3	
825°C	32,700	0.3	--	--	0.8	
860°C	31,900	0.1	0.8	1.6	0.2	38.0
860°C	30,100	0.5	2.8	4.1	1.8	44.5
860°C	31,600	0.2	1.2	1.6	0.5	42.5
860°C	33,000	1.0	--	--	0.3	
900°C	33,100	0.1	0.8	1.6	0.0	42.1
900°C	34,100	0.2	1.2	2.4	0.0	42.1
900°C	30,300	0.2	0.8	0.8	0.7	40.7

*Yield Strength 29,500 psi

as great. The fusion weld tensiles reported in these tables were cut from as-welded 1/8-inch beryllium sheet in which the welds had been made with 0.090-inch drawn wire. These tensiles were then separately heat treated in our physical testing laboratory.

The indication is that longer time at temperature does not improve the tensile strength or ductility of the welds (Table III), but that higher temperature (at least to 825°C) does increase the tensile strength of the welds. For plates fusion welded from rolled stock, no significant increase in strength is apparent as a result of an increase of heat-treatment temperature above 825°C. Although mechanical properties of the heat treated weld are not significantly improved over that of the as-welded conditions, the post-heat treatment is important in the welding operation, because the as-welded tensiles have less elongation on the average than do the tensiles that have been heat treated at 825°C or above.

In comparing the post heat treatment results data from Table IV with those in Table V, one notices that the tensile strengths of the welds made longitudinally to the direction of last rolling of the sheet are significantly less than those made transversely to the last rolling direction. All of the welds made for which the tensile data were reported were made of the same base parent metal, 202-1-6003, but may have varied in orientation and grain structure, since the metal did not all come from the same rolled sheet. Many tensiles in addition to those reported in Table V were made on metal welded longitudinally to the direction of rolling, and they averaged around 28,000 psi ultimate strength, as compared with over 30,000 psi reported in Table V for metal welded transversely to the direction of rolling. This is the first time that physical properties have been noted to vary according to the rolling orientation of the sheet being welded. The sheets used in this program are of a higher orientation than sheets previously used for fusion welding studies. These welds made transverse to the rolling direction on high oriented sheets show a higher strength than those made longitudinal to the rolling direction.

3. Multiple Pass Welding, T-Welds, Fixturing, etc.

With the welding of 1/4-inch-thick beryllium successful, initial work on heavy weldments was begun with an attempt to weld 1/2-inch-thick beryllium in one pass. This failed because the high-current density required caused considerable oxidation and turbulence.

TABLE V

POST HEAT TREATMENT STUDIES OF FUSION WELDS - LONGITUDINAL WELDS

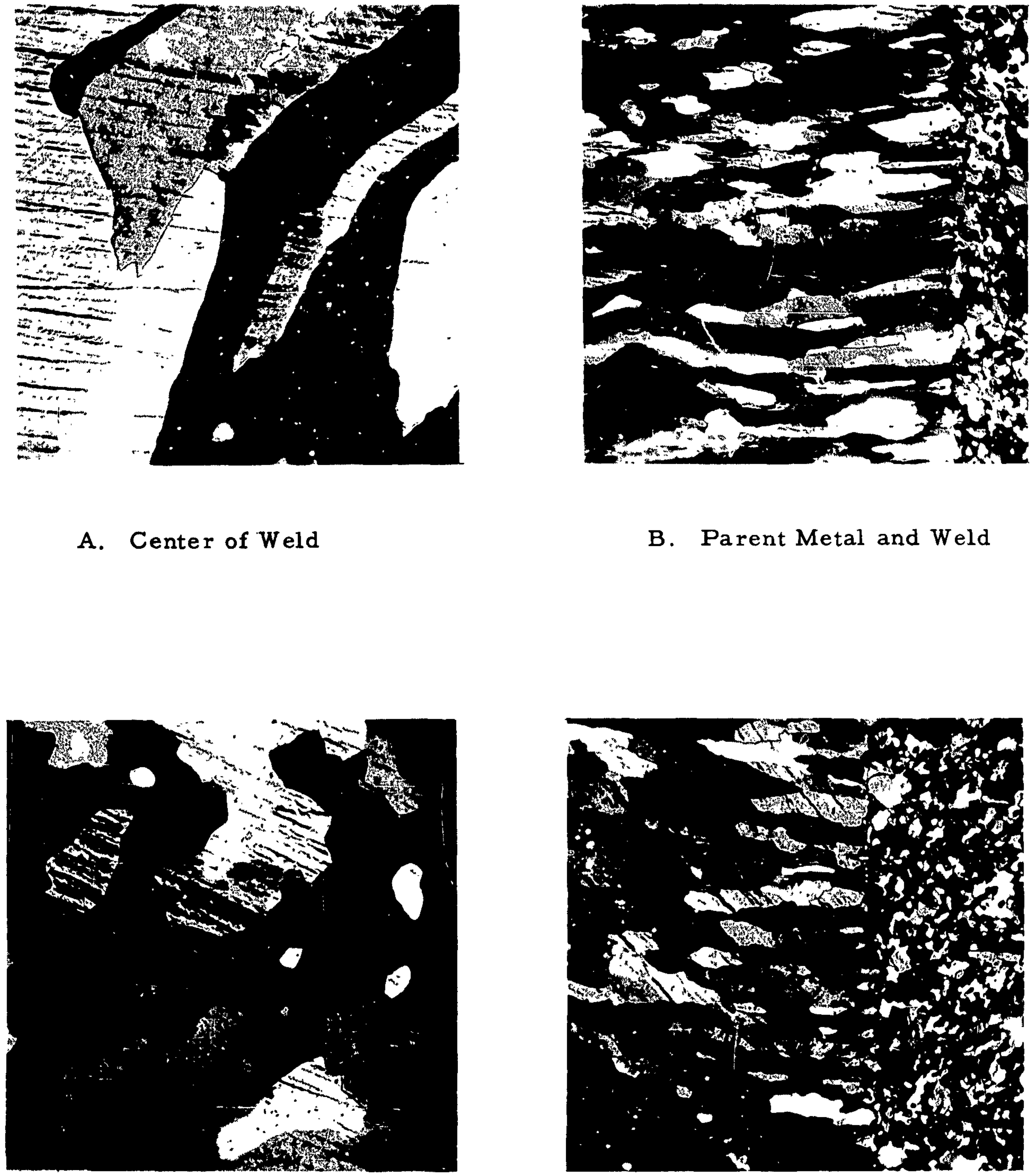
Post Heat Treatment	Tensile Strength (psi)	Contraction (%)	Elongation in 2 inches (%)
As-Welded	29,100	0.6	0.0
860°C	28,700	0.4	0.5
900°C	28,200	0.4	0.1

It appears from this work that when our present welding technique is used, 200 amperes is about the maximum feasible current density for manual welding of beryllium. Therefore, multiple pass welding was tried. Although most of our multiple pass welding of thick sections has resulted in microcracks, some successful welds have been made where short lengths of 1/2- and 3/4-inch thicknesses were welded in less than seven passes. The 1/2- and 3/4-inch-thick beryllium metal used for this initial study was from four to eight years old.

None of the attempts to fusion weld 1-inch-thick by 4-inch wide by 8-inch-long beryllium blocks by multiple-pass techniques were successful. This was due primarily to microcracks found transverse to the direction of welding, which can be traced down to the base beryllium metal. It was thought preheating might enhance the chance of s successful multiple pass welding, and although test results gave some indication that this is true, no successful welds have been made in 1-inch-thick beryllium metal. Probably, this was because larger grains were grown than normally occur.

Photomicrographs of one of the successful multiple pass short welds were prepared (Figure 16). Although most of the passes show fairly fine grains, two internal passes show excessive grain growth. The reason for the grain size variation from one pass to another is not readily explained unless one considers the secondary passes to have been laid down under an excessively preheated condition owing to the fact that the metal was not allowed to cool sufficiently between passes. It appears from this work that further studies will be necessary to determine: (1) The cause of transverse microcracks and (2) The cause of the exceptionally large grains found on certain internal multiple passes in the heavy weldments.

Using the multiple pass welding technique as developed under this program, attempts were made to weld a cracked beryllium ring, which is about 5/8-inch thick at one point. This presented quite a problem, since the thickness varied from 1/8 inch to 5/8 inch, requiring variable current density plus multiple passes. Five passes were needed to fill the gap of the thickest section in repairing the cracked ring; the ring was then cleaned (Figure 17). When the ring was checked with Zyglo, microcracks which appeared in the edge of the weld transverse to the direction of welding propagated up through the weld from an area in the parent metals adjacent to the weld zone. Although this welding was



A. Center of Weld

B. Parent Metal and Weld

C. Center of Weld

D. Parent Metal and Weld

Fig. 16 - Cross Sections of Multiple Pass Beryllium Fusion Welds, 100X

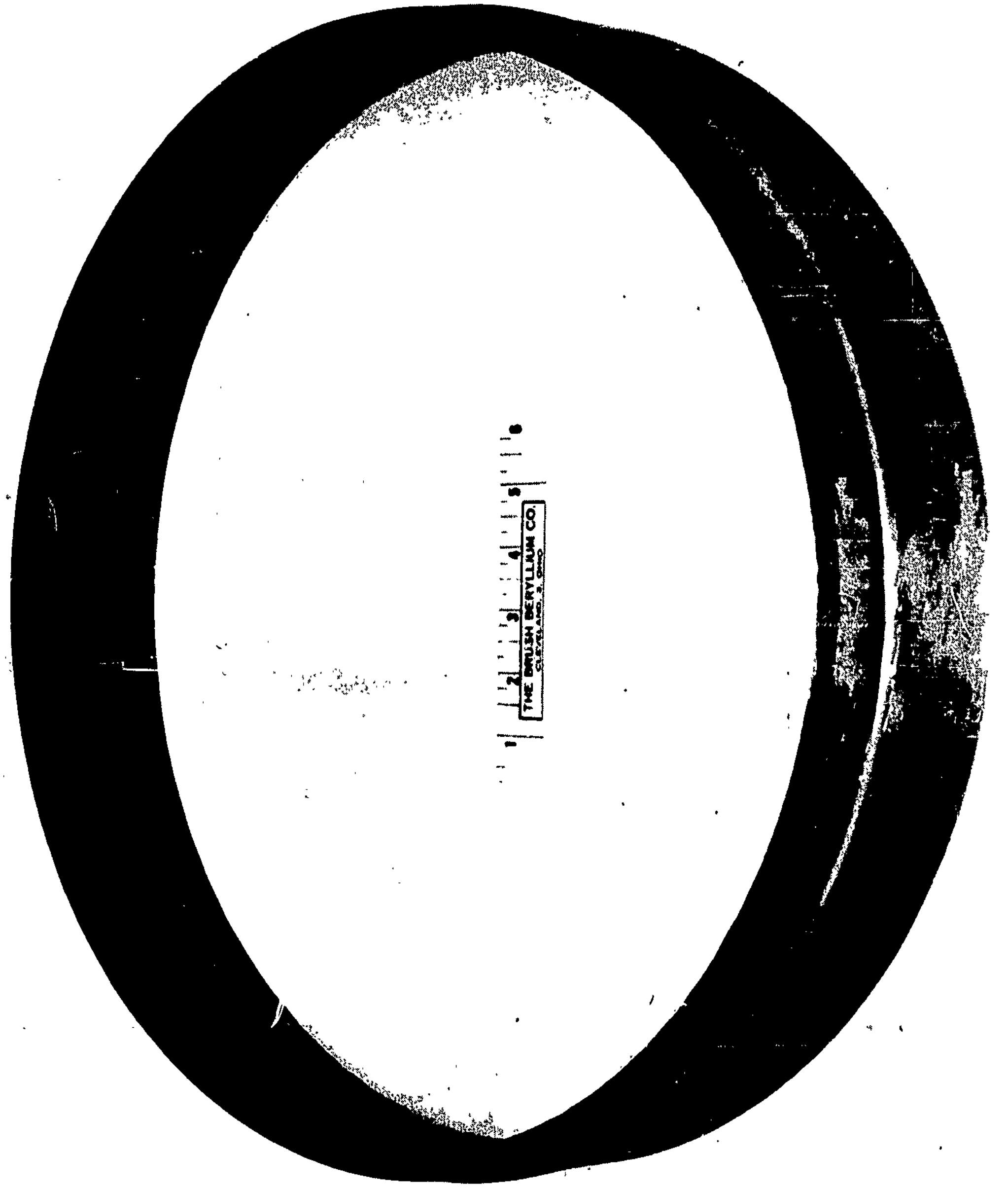


Fig. 17 - Repair Attempted on a Cracked Beryllium Ring by the Multipass Fusion Welding Technique

not successful, it does show promise that thick sections will be welded, since we have noted no major cracking as would be indicated by previous work.

In the welding of T-joints with 1/8-inch and 1/4-inch-thick beryllium, it appears that the best results were obtained by fillet welding on both sides of the T-joints. The major problem, obtaining root penetration, in making a fillet weld in beryllium is a quite difficult one because the high thermal conductivity and high specific heat of the metal cause a chilling and rapid quenching effect. To obtain root penetration, welding with small diameter tungsten and 0.032-inch-diameter beryllium wire was attempted. Although a smoother, much better looking weld was obtained, penetration in the fillet weld was not adequate. Another unsuccessful approach was an attempt to reach 100% penetration from one side and then to add the least possible amount of fillet on the secondary side. Attempts to burn through or use excessive amperage in order to obtain root penetration resulted in porosity and cracking. Except for the lack of penetration, sound fillet welds have been made in 1/8-inch to 1/8-inch joints and 1/8-inch to 1/4-inch-thick joints. Some multiple-pass welds have been successful with this type of fillet welding, but were not reproducible. These fillet welds of T-joints appear to have a finer grain structure in the cast weld metal than do the butt-type joints.

Throughout this development work, proper fixturing has been shown to be critical to the weldability of beryllium, since improper fixture materials can cause cracking, porosity, and other undesirable properties in the weld. The backup material on the fixture comes in contact with the molten metal of the weld and it is important that the backup material react as little as possible with the molten metal.

Original welding fixtures for this manual welding of beryllium were made of micarta, asbestos, and aluminum oxide blocks. In an effort to improve fixturing, stainless steel, copper, and graphite were coated with non-thermal conducting materials and compared as weld backup material with non-thermal conducting materials in solid block or sheet form. A hot-spray coating of aluminum oxide on copper is not satisfactory as it spalls if the coating gets too thick (owing to the differences in thermal expansion and contraction of the two materials). Also, with thin coatings on copper an adequate thermal insulating layer is not formed between the two materials, and cracking occurs in the beryllium owing to thermal shock.

Both stainless steel and graphite have lower thermal conductivity than does copper, and each has shown some degree of success as a backup material when coated with thermal-sprayed aluminum oxide. Stainless steel fixtures of the automatic unit which had been sprayed with a 0.005-

inch-thick coating of aluminum oxide were satisfactory for welding beryllium up to 1/8-inch thick. They were not satisfactory for welding 1/4-inch-thick beryllium sheet.

Graphite was chosen as a backup material for some studies, since under normal conditions it can be machined easily and produced cheaply for odd-job welding. Although both stainless steel and graphite coated pieces are good for welding thin sections of beryllium (1/8 inch or less), they are unsatisfactory for welding thicker sections of beryllium because of the thermal shock problem. Nevertheless, for sections thicker than 0.060 inch, a solid oxide block should be used as a backup material in the immediate area under the weld. With such a backup used, the problem would remain of protecting the underneath side of the weld from oxidation during fusion welding by the TIG method. This underneath protection can be accomplished by two methods: (1) by diffusing the inert gas through coarse aluminum oxide backup or (2) as is normally done, by welding inside an enclosure filled with inert gas.

A new hood, which was built around the automatic head, was designed so that less draft can be used on the hood. As additional protection, a second inert gas shield was placed around the automatic head. With these changes, which tended to improve the stability of the arc, successful automatic welds, both with and without beryllium filler metal, have been made using a DC straight polarity power source. With welding conditions on the automatic head thus improved, more uniform welds should be made in beryllium.

Using drawn beryllium filler wire, successful welds have been made on beryllium joints by the metal-arc inert-gas (MIG) welding process. The grain size of the metal arc weld was 24 microns in the parent metal and 129 microns in the center of the weld zone. Welds made by the high speed MIG process gave much finer grains in the weld zone, although microcracking occurred.

B. Beryllium Filler Wire Development Phase

In this program, beryllium filler-wire development was started by mixing various additions of alloying elements (basically those impurity elements which are normally found in beryllium metal, along with germanium) with -200 mesh QMV[a] beryllium powder. In Table VI are shown the initial analyses, as well as the chemical composition and density of the beryllium alloy billets after the standard beryllium hot-pressing operation. These hot-pressings were then machined into extrusion billets.

[a]All beryllium powder used in this phase was from heat Y-5191, with the exception of the nominal 2% and 3% oxide beryllium powder (Samples 3 and 4, Table VI).

TABLE VI

BERYLLIUM FILLER WIRE DEVELOPMENT PHASE

Sample No.	Element Addition	Initial Element Analysis (%)	Element Analysis After Pressing (%)	Initial BeO (%)	BeO After Pressing (%)	Theoretical Density (g/cc)	Pressed Density (g/cc)
1	Mg	1.05	0.006	0.77	1.32	1.85	1.84
2	Mg	2.04	0.006	0.77	1.13	1.85	1.76
3	--	--	--	1.83	1.99	1.86	1.86
4	--	--	--	--	3.11	1.88	1.84
5	Al	1.02	0.18	0.77	0.99	1.87	1.81
6	Al	2.03	0.22	0.77	1.05	1.88	1.81
7	Fe	0.45	0.61	0.77	1.01	1.89	1.64
8	Fe	1.08	1.05	0.77	1.05	1.92	1.86
9	Si	1.19	0.16	0.77	1.06	1.86	1.84
10	Si	2.49	0.18	0.77	0.88	1.87	1.84
11	SiO_2	0.40	0.14	0.77	1.38	1.86	1.85
12	Ge	7.37	3.7	0.77	1.35	2.12	1.90
13	Control	--	--	0.77	1.36	1.85	1.76
14	Control	--	--	0.77	0.96	1.85	1.83
15	Control	--	--	0.77	0.94	1.85	1.84

Although 1/8-inch diameter warm extrusions of controlled beryllium metal have been made, it was impractical to produce alloyed beryllium wire by the warm extrusion method because of die design economics. Therefore, our Fabrication Section developed a swaging method to swage the machined billets into 1/8-inch wire. This wire was then used to weld 1/8-inch virgin beryllium sheets together.

Results of the welding operation are reported in Table VII, and the mechanical properties of the welds are given in Table VIII. Table IX shows the average grain size of these welds and Table X gives the analyses of the welds as compared to the analyses of the wire used. Figures 18 through 29 are photomicrographs of the cross section of the welds made in this phase of the program.

The first significant observation relating to the samples is the very heavy porosity in the second magnesium sample to which over 2% magnesium was added before pressing. Without doubt, the porosity is the heaviest encountered in our welding operation, although the magnesium content indicated by analysis is less than what is normally found in the hot-pressing of beryllium. It was assumed that after the hot-pressing operation, all of the magnesium added to the pressing had vaporized off. However, magnesium must still have been present in the welding wire which was not accounted for in the pressing analysis. The chemical analysis of the weld made with sample #2 wire shows a higher magnesium content than the wire used. Sample #3 (with the nominal 2% BeO level) welded as would be expected with virgin material. The high-oxide material, containing more than 3% BeO, was poor in both weldability and X-ray results, although the weld was acceptable except for high-density spots. It is interesting to note that in this particular specimen, the oxide level dropped from above 3% before welding to less than 1% in the weld metal after welding (Table X). The chemical analysis of the nominal 2% oxide beryllium was similar to that of Y-5191, whereas the chemical analysis of the nominal 3% oxide beryllium was poor, and the poor welding results with the 3% oxide beryllium could be caused by elements other than beryllium oxide.

The aluminum-containing specimens, which had a higher aluminum content than control metals, welded normally, if not slightly better than normally. The iron samples displayed microcracks and high-density spots and were poor in weldability, as would be expected from the coated wire results reported in the following section of this report. The silicon additive resulted in a very interesting improvement in the weldability of the specimen - that of increasing the flowing and ease with which one can make a weld in beryllium. The X-ray results also were good.

Although silicon oxide seemed to improve the weldability as had silicon, the weld itself was not quite as good in outward physical appearance

TABLE VII

ANALYSIS OF WELDABILITY WITH BERYLLIUM ALLOY WIRE

Sample No.	Element Addition	Pressing Analysis (%)	Weldability	Soundness (radiography)	Comment on Weld
1	Mg	0.006	Normal	Good	
2	Mg	0.006	Poor	Poor	Heavy porosity Heavy oxidation
3	BeO	1.99	Normal	Good	
4	BeO	3.11	Poor	Poor	High density spot
5	Al	0.18	Normal	Good	
6	Al	0.22	Normal	Good	
7	Fe	0.61	Poor	Poor	Microcracks High density spots
8	Fe	1.05	Poor	Poor	High density spots
9	Si	0.16	Excellent	Good	
10	Si	0.18	Excellent	Good	
11	SiO_2	0.14	Excellent	Fair	One high density spot
12	Ge	3.7	Poor	Poor	High density weld

TABLE VIII

MECHANICAL PROPERTIES OF WELDS FROM BERYLLIUM FILLER WIRE DEVELOPMENT PHASE

Sample No.	Ult. Str. (psi x 10^3)	Modulus (psi x 10^6)	Cont. (%)	Elongation in 1/8 in. (%)	Elongation in 1/4 in. (%)	Elongation in 2 in. (%)	Initial Alloy Addition
1	30.9	--	1.1	--	--	--	1.05% Mg
	35.2	40.6	0.6	1.2	0.8	0.1	
	25.4	--	0.0	1.5	1.1	0.2	
2	29.6	--	0.0	3.4	1.7	0.2	2.04% Mg
	Broken	--	--	--	--	--	
	28.4	45.4	0.0	2.4	1.2	0.4	
3	32.3	--	0.3	2.3	1.7	0.3	1.83% BeO
	34.6	--	0.8	3.5	1.9	0.3	
	21.8*	--	0.2	0.8	0.6	0.1	
4	20.1	40.1	0.2	3.1	1.5	0.2	3.11% BeO
	29.2	--	0.2	5.0	2.7	0.4	
	21.9	44.0	0.1	3.1	1.5	0.2	
5	28.9	40.2	0.07	--	--	--	1.02% Al
	30.1	40.6	0.2	0.7	0.7	0.1	
	32.8	41.6	0.4	0.6	0.6	0.1	
6	34.3	--	0.1	2.4	1.2	0.2	2.03% Al
	30.3	--	0.0	2.5	1.3	0.3	
	29.5	--	0.4	2.4	1.2	0.2	
7	24.2	40.2	--	--	--	--	0.45% Fe
	29.5	48.9	--	--	--	--	
	15.7	--	--	--	--	--	
8	31.7	--	0.8	3.1	1.7	0.2	1.08% Fe
	31.8	--	0.0	--	--	--	
	25.1	43.1	0.0	--	--	--	
9	27.5	45.1	0.1	--	--	--	1.19% Si
	27.8	--	--	--	--	--	
	30.3	43.3	0	--	--	--	
10	32.0	--	0.5	3.2	1.6	0.2	2.49% Si
	22.2	--	0.1	1.6	0.8	0.1	
	30.1	--	0.2	2.0	1.0	0.2	

(Continued)

TABLE VIII (Continued)

MECHANICAL PROPERTIES OF WELDS FROM BERYLLIUM FILLER WIRE DEVELOPMENT PHASE

Sample No.	Ult. Str. (psi x 10^3)	Modulus (psi x 10^6)	Cont. (%)	Elongation in 1/8 in. (%)	Elongation in 1/4 in. (%)	Elongation in 2 in. (%)	Initial Alloy Addition
11	Tensiles broken prior to testing						0.40% SiO
12	26.8	40.6	0.4	1.6	0.8	0.1	7.37% Ge
	30.9	41.2	0.3	--	--	--	
	29.8	44.4	0.4	--	--	--	
Control	30.3	--	0.04	--	--	--	
	30.9	42.7	0.2	2.2	1.9	0.3	

*Broke in Wedge.

TABLE IX

AVERAGE GRAIN SIZE OF WELDS FROM BERYLLIUM FILLER WIRE DEVELOPMENT PHASE

Sample No.	Parent Metal Average Grain Size μ	Fusion Weld Average Grain Size μ	Initial Alloy Addition
1	29	91	1.05% Mg
2	43	90	2.09% Mg
3	43	107	1.83% BeO
4	34	91	3.11% BeO
5	27	128	1.02% Al
6	40	91	2.03% Al
7	34	107	0.45% Fe
8	25	91	1.08% Fe
9	27	80	1.19% Si
10	34	107	2.49% Si
11	32	80	0.40% SiO
12	30	91	7.37% Ge
Control	27	91	--------

TABLE X

CHEMICAL ANALYSIS OF FUSION WELDS FROM THE BERYLLIUM FILLER WIRE DEVELOPMENT PHASE

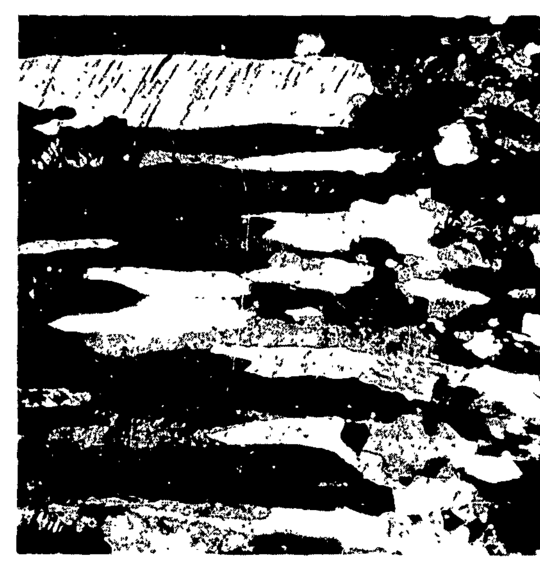
Plate No.	Sample No.	Element Addition	Analysis of Wire (%)	Analysis of Weld (%)
13	1	Mg	0.006	0.003
2	2	Mg	0.006	0.008
11	3	BeO	1.99	1.06
15	4	BeO	3.11	0.88
8	5	Al	0.18	0.11
6	6	Al	0.22	0.15
3	7	Fe	0.61	0.25-0.35
12	8	Fe	1.05	0.43
4	9	Si	0.16	0.05-0.10
5	10	Si	0.18	0.055
14	11	SiO_2	0.14	0.08
9	12	Ge	3.7	0.1-1.0
	13	Control	--	--
	14	Control	--	--
	15	Control	--	--

A. Center of Weld

B. Parent Metal and Weld

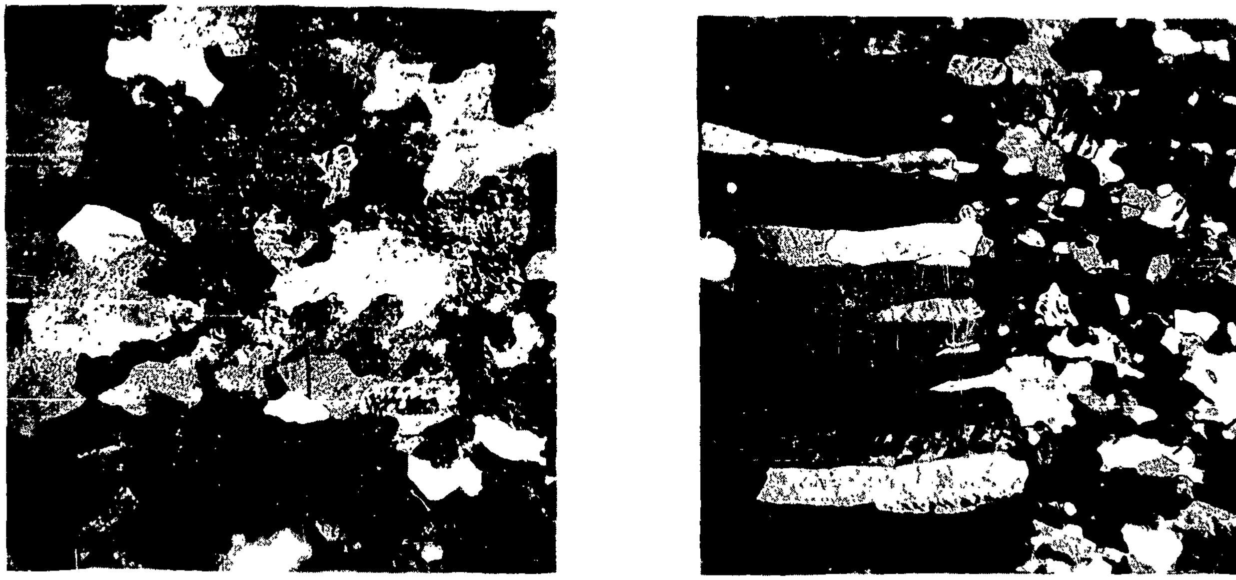
Fig. 18 - Cross Section of Fusion Weld Made with Magnesium Containing Beryllium Filler Wire (Sample No. 1), 100X

A. Center of Weld



B. Parent Metal and Weld

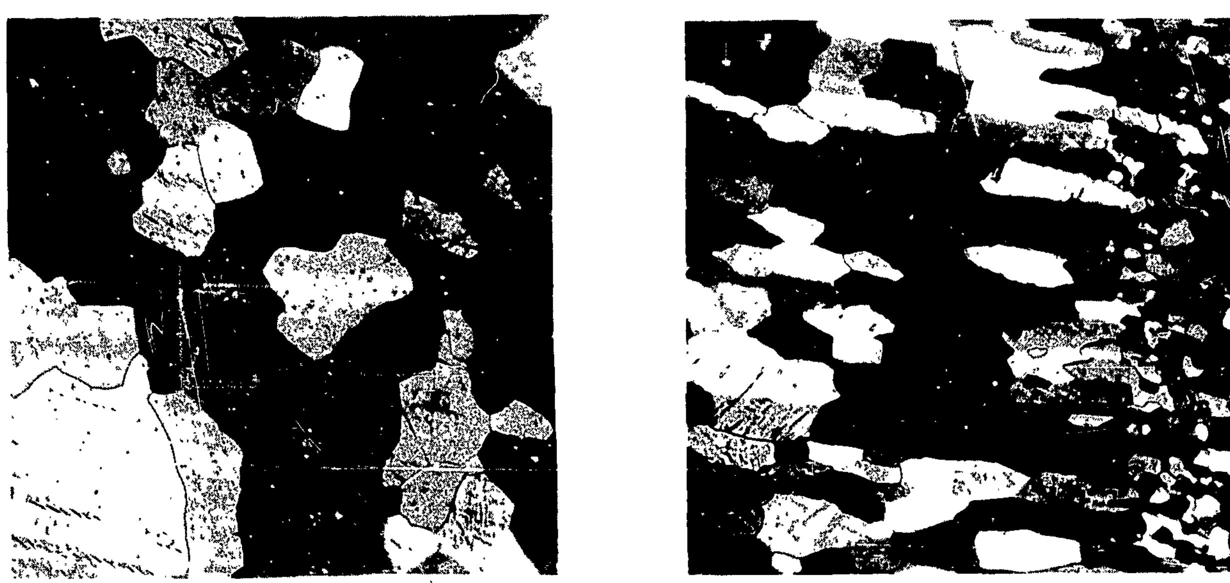
Fig. 19 - Cross Section of Fusion Weld Made with Magnesium Containing Beryllium Filler Wire (Sample No. 2), 100X



A. Center of Weld

B. Parent Metal and Weld

Fig. 20 - Cross Section of Fusion Weld Made with Nominal 2% BeO Beryllium Filler Wire (Sample No. 3), 100X



A. Center of Weld

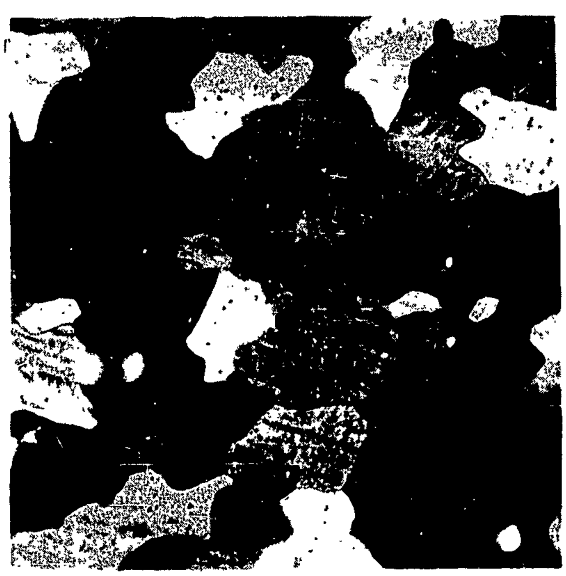
B. Parent Metal and Weld

Fig. 21 - Cross Section of Fusion Weld Made with Nominal 3% BeO Beryllium Filler Wire (Sample No. 4), 100X

A. Center of Weld

B. Parent Metal and Weld

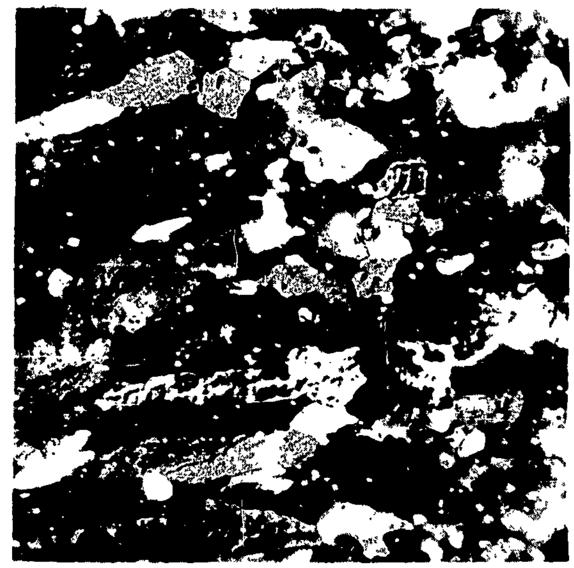
Fig. 22 - Cross Section of Fusion Weld Made with Aluminum Containing Beryllium Filler Wire (Sample No. 5), 100X



A. Center of Weld

B. Parent Metal and Weld

Fig. 23 - Cross Section of Fusion Weld Made with Aluminum Containing Beryllium Filler Wire (Sample No. 6), 100X



A. Center of Weld

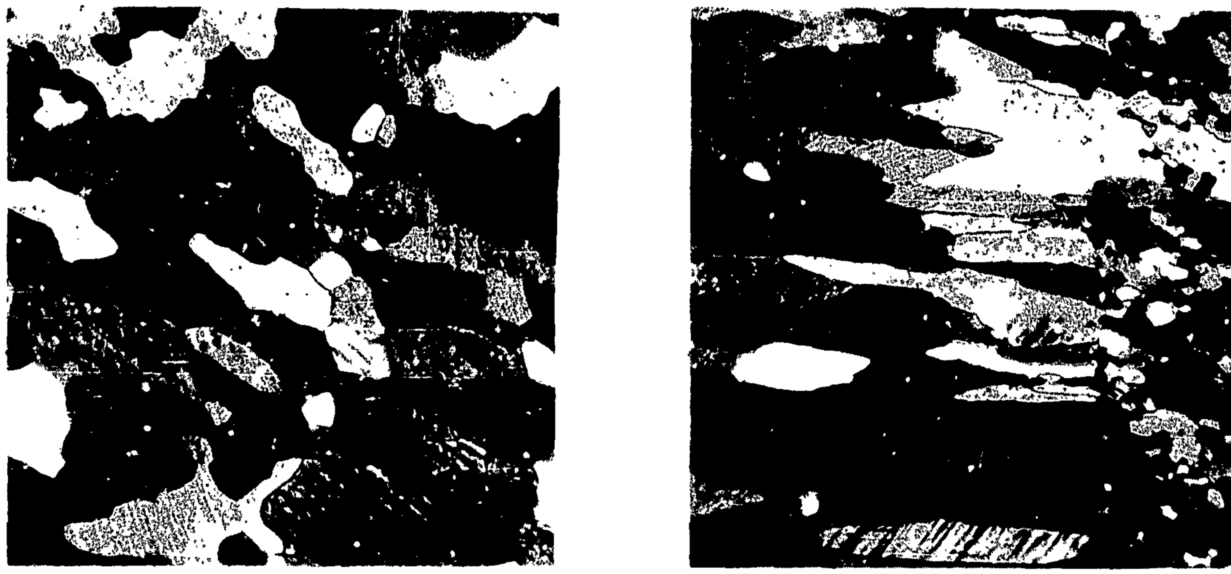
B. Parent Metal and Weld

Fig. 24 - Cross Section of Fusion Weld Made with Iron Containing Beryllium Filler Wire (Sample No. 7), 100X

A. Center of Weld

B. Parent Metal and Weld

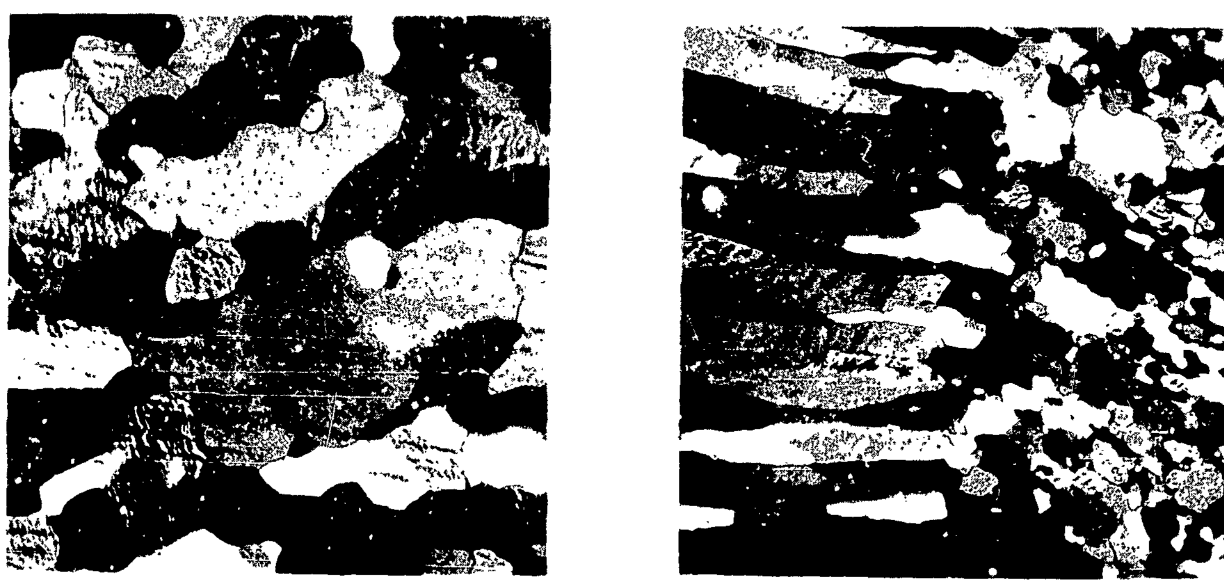
Fig. 25 - Cross Section of Fusion Weld Made with Iron Containing Beryllium Filler Wire (Sample No. 8), 100X



A. Center of Weld

B. Parent Metal and Weld

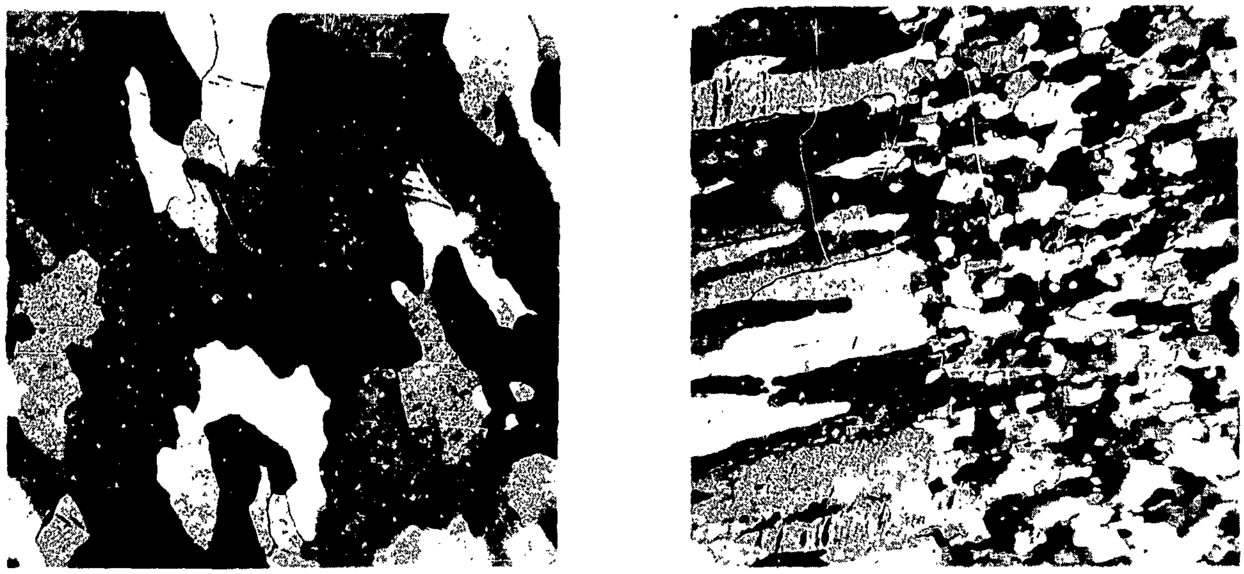
Fig. 26 - Cross Section of Fusion Weld Made with Silicon Containing Beryllium Filler Wire (Sample No. 9), 100X



A. Center of Weld

B. Parent Metal and Weld

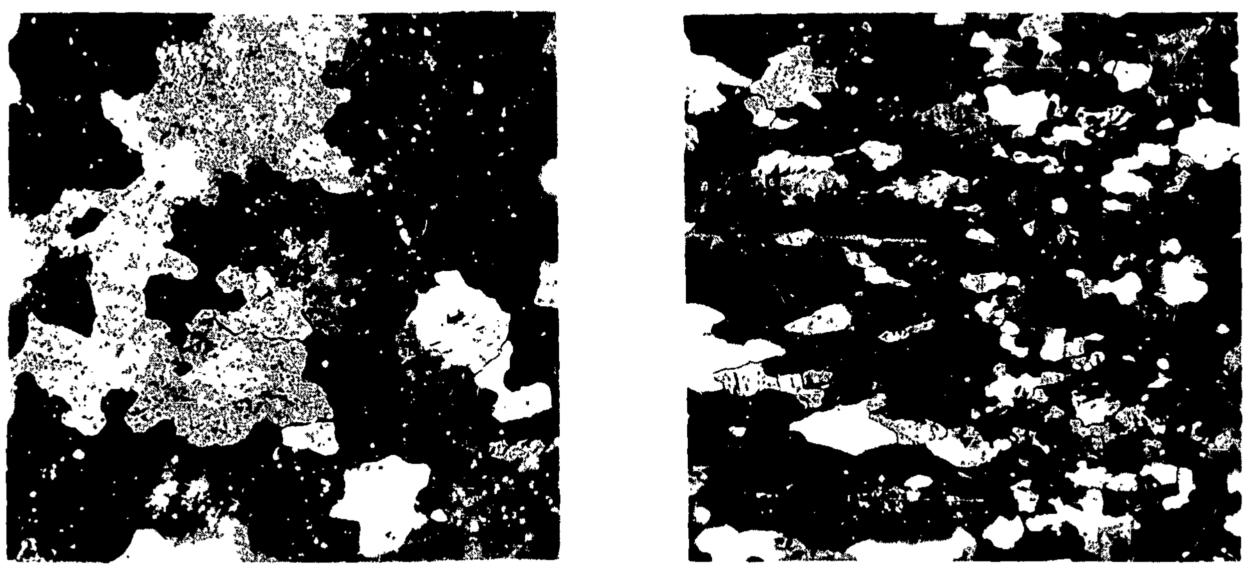
Fig. 27 - Cross Section of Fusion Weld Made with Silicon Containing Beryllium FillerWire (Sample No. 10), 100X



A. Center of Weld

B. Parent Metal and Weld

Fig. 28 - Cross Section of Fusion Weld Made with Silicon Oxide Containing Beryllium Filler Wire (Sample No. 11), 100X



A. Center of Weld

B. Parent Metal and Weld

Fig. 29 - Cross Section of Fusion Weld Made with Germanium Containing Beryllium Filler Wire (Sample No. 12), 100X

or in X-ray appearance, and all of the weld tensiles broke in machining. Germanium addition made the beryllium wire quite difficult to weld with, and the weld appearance (both outward and internal) was poor.

C. Coated Beryllium Wire

Drawn beryllium welding wire was coated with copper, silver, gold, nickel, iron, cobalt, tin, chromium, zinc, and cadmium to study the effects of these elements upon the fusion welding of beryllium. Welds made with gold-, iron-, and chromium-coated wires fractured during welding, and the welds made with cobalt-, nickel-, and copper-coated wires fractured after the welds were completed. Crack-free welds were made with silver-, tin-, zinc-, and cadmium-coated beryllium wires. It is interesting to note, from Figures 30 through 38, that those welds which cracked show highly stressed microstructures, whereas the welds made with cadmium, zinc, and tin did not show these highly stressed microstructures but showed a microstructure similar to beryllium. Welds made with iron-coated wire, which were the poorest of the welds studied, have a laminar structure (as shown in Figure 30). In several of the photomicrographs, such as those showing the chromium-, silver-, and nickel-containing beryllium, there is a stronger network present which does not cross present grain boundaries. This secondary network is obviously not grained.

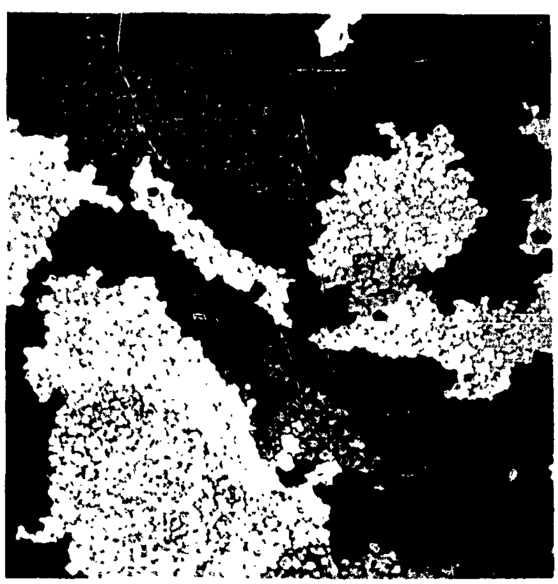
Since crack-free welds were made with silver-, tin-, cadmium-, and zinc-coated beryllium wire, sheet-metal tensiles were made from these welds, with results reported in Table XI. The chemical analyses of these fusion welds are reported in Table XII. Although silver-coated wire caused a secondary network in the beryllium welds, silver does not form intermetallics with beryllium as has been determined by X-ray diffraction studies of the welds, and the welds were crack-free. Wires coated with silver seem to deter the weldability of beryllium; and the use of silver in the weldment does not seem to improve the tensile properties of a weld, as had been anticipated. Although cold shot appeared at the fracture in two of the welded tensiles, it did not seem to affect the strength of these welds made with silver-coated wires.

As noted in the micrographs of tin, zinc, and cadmium, additions of these elements do not appear to affect the grain structure of beryllium weldment. Some tin-coated wires have a tendency toward microcracking at the edge of the weld. Some farily good tensile strengths were obtained, although two of the tensiles did break in microcracks, showing lowered tensile strengths. This tendency to microcrack, which was not common for all of the tin-coated wires, may have been due to some secondary material used to plate the tin onto the beryllium wire. Tin appears to be

A. Center of Weld

B. Parent Metal and Weld

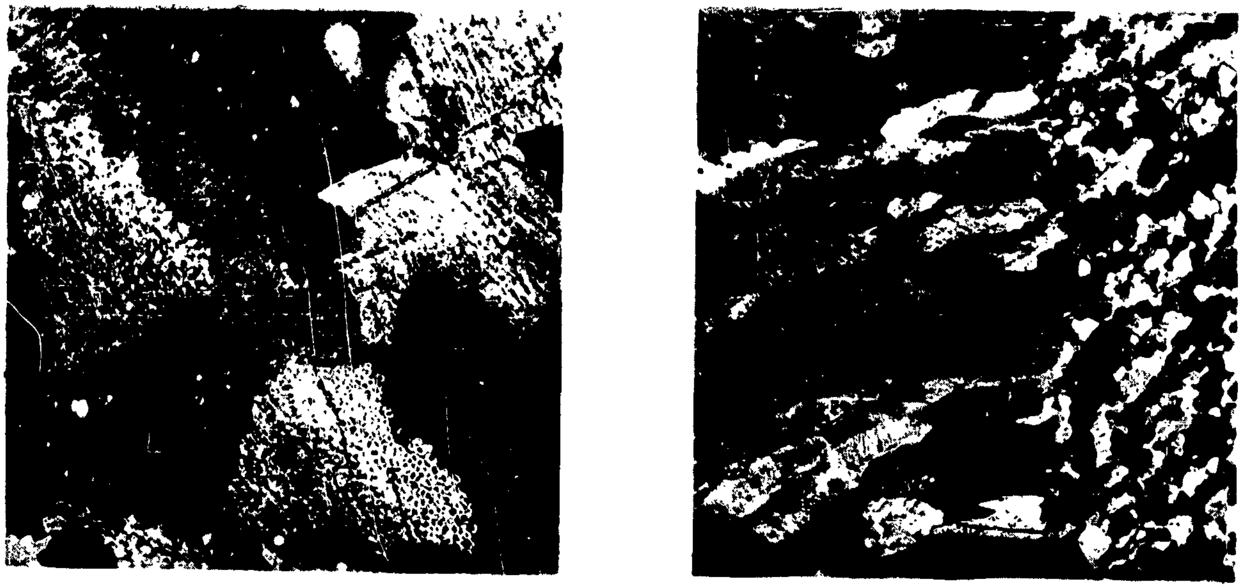
Fig. 30 - Cross Section of Fusion Weld Made with Iron-Coated 1/8-Inch-Diameter Drawn Beryllium Wire, 100X



A. Center of Weld

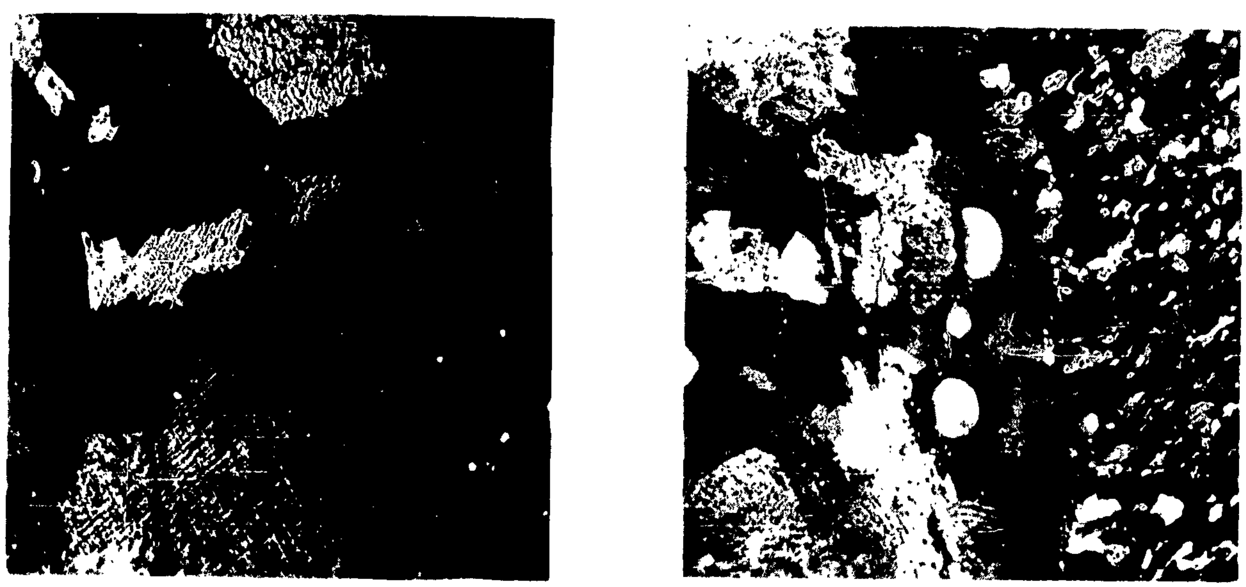
B. Parent Metal and Weld

Fig. 31 - Cross Section of Fusion Weld Made with Chromium-Coated 1/8-Inch-Diameter Drawn Beryllium Wire, 100X



A. Center of Weld B. Parent Metal and Weld

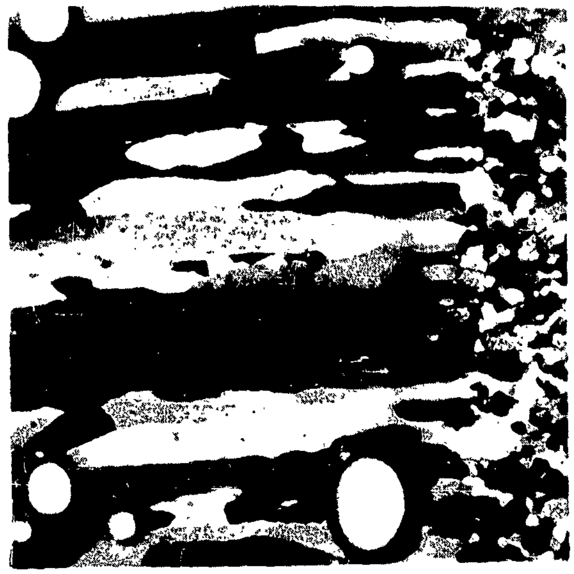
Fig. 32 - Cross Section of Fusion Weld Made with Nickel-Coated 1/8-Inch-Diameter Drawn Beryllium Wire, 100X



A. Center of Weld B. Parent Metal and Weld

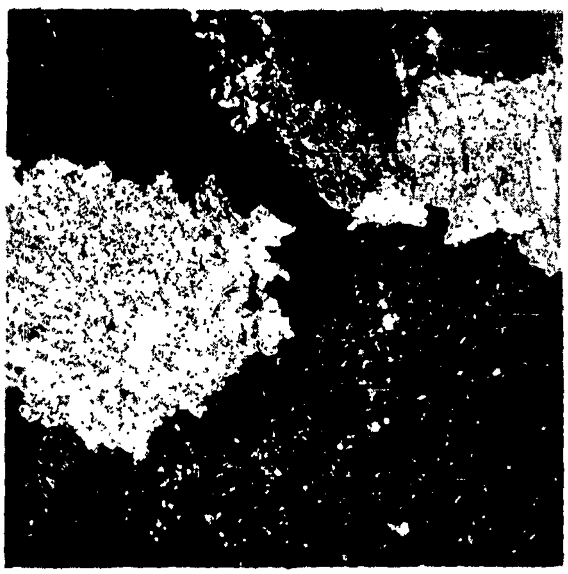
Fig. 33 - Cross Section of Fusion Weld Made with Cobalt-Coated 1/8-Inch-Diameter Drawn Beryllium Wire, 100X

A. Center of Weld

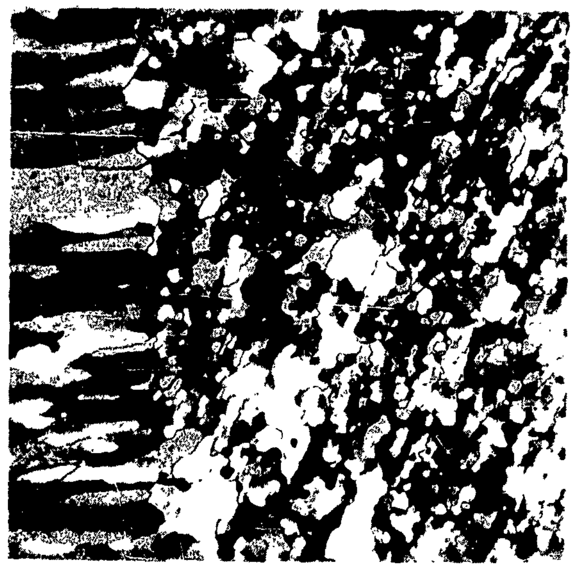


B. Parent Metal and Weld

Fig. 34 - Cross Section of Fusion Weld Made with Copper-Coated 1/8-Inch-Diameter Drawn Beryllium Wire, 100X

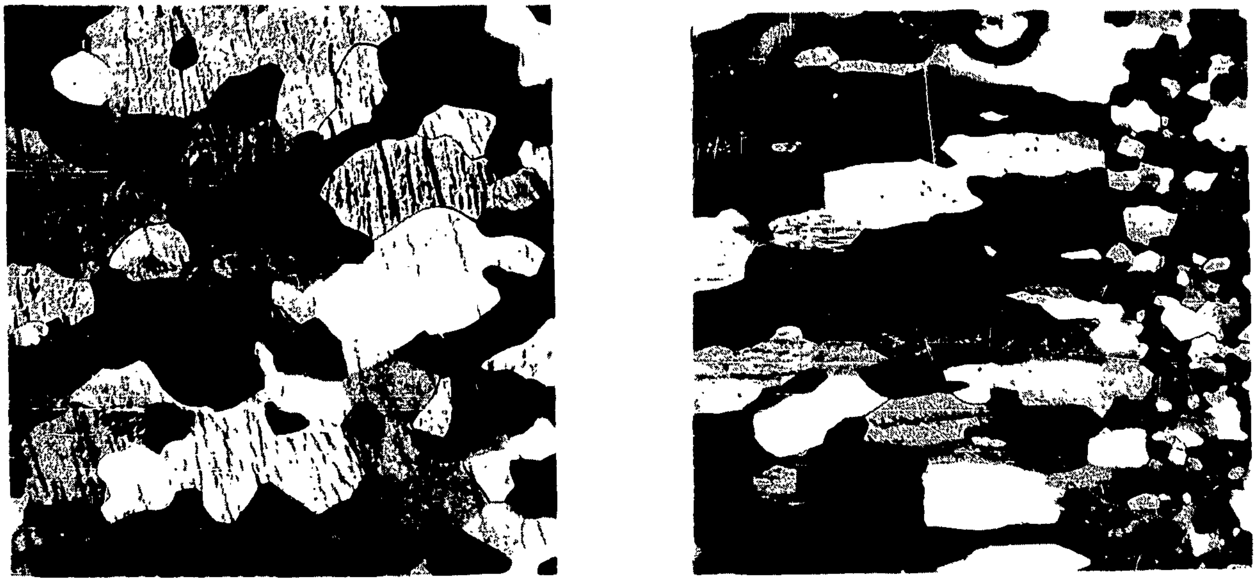


A. Center of Weld



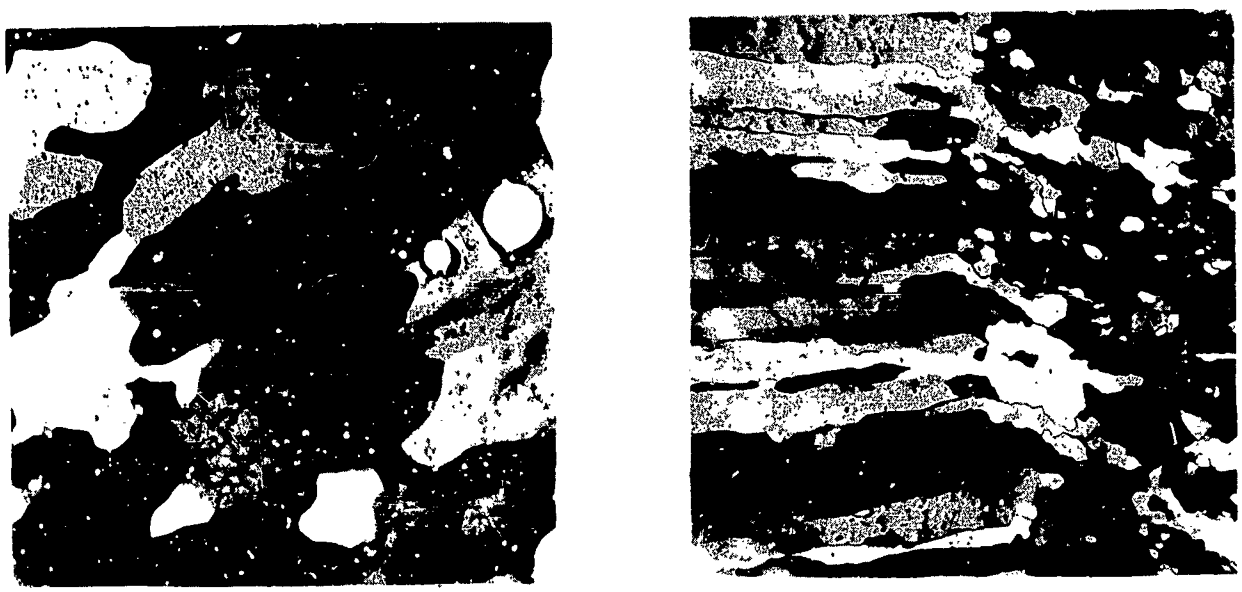
B. Parent Metal and Weld

Fig. 35 - Cross Section of Fusion Weld Made with Silver-Coated 1/8-Inch-Diameter Drawn Beryllium Wire, 100X



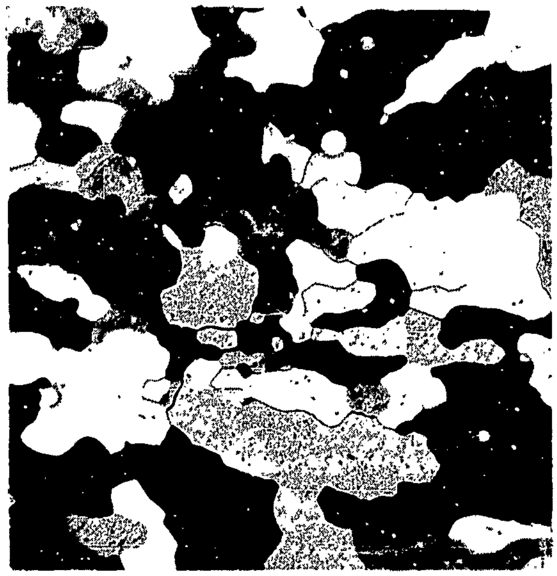
A. Center of Weld B. Parent Metal and Weld

Fig. 36 - Cross Section of Fusion Weld Made with Tin-Coated 1/8-Inch-Diameter Drawn Beryllium Wire, 100X



A. Center of Weld B. Parent Metal and Weld

Fig. 37 - Cross Section of Fusion Weld Made with Zinc-Coated 1/8-Inch-Diameter Drawn Beryllium Wire, 100X



A. Center of Weld

B. Parent Metal and Weld

Fig. 38 - Cross Section of Fusion Weld Made with Cadmium-Coated 1/8-Inch-Diameter Drawn Beryllium Wire, 100X

TABLE XI

MECHANICAL PROPERTIES OF FUSION WELDS MADE WITH COATED BERYLLIUM WIRE

Electrode Coating	Tensile Strength	Elongation in 2 inches (%)	Fracture[a]
Silver	32,600	0.0	Foreign inclusion
Silver	30,600	0.3	In parent metal
Silver	28,600	0.0	
Silver	27,200	0.0	
Silver	31,000	0.0	Foreign inclusion
Average	30,000		
Tin	30,700	0.0	
Tin	32,700	0.0	
Tin	33,300	0.2	
Tin	32,500	0.0	
Tin	25,800	0.0	
Tin	26,700	0.0	
Tin	31,500	0.2	
Average	30,500		
Zinc	35,300	0.2	
Zinc	30,600	0.0	
Zinc	28,000	0.2	Porosity in weld
Zinc	29,800	0.0	Porosity in weld
Zinc	32,100	0.0	Porosity in weld
Average	31,100		
Cadmium	27,300	0.0	
Cadmium	28,300	0.0	
Cadmium	29,700	0.3	
Average	28,400		

[a]Except for one tensile noted to have fractured in the parent metal, all welds fractured at the weld center line.

TABLE XII

CHEMICAL ANALYSIS OF FUSION WELDS MADE WITH COATED BERYLLIUM WIRE

Weld Wire Coatings	Weld Analysis of coating element (wt. %)	Weld BeO Analysis (%)
Silver	26.1	1.58
Tin	0.41	0.48
Zinc	0.01	0.63
Cadmium	0.00002	0.58

a good coating material for beryllium since it neither alloys with, nor is appreciably retained in the beryllium. It was found as small pebbles under the weld, separated by gravity segregation.

Although welds were made with zinc-coated wire, they appeared to be unsatisfactory. The outgassing was so extensive that the work could not be seen during welding. This is indicated by the porosity in the zinc metallographic specimen which did not, however, appear to affect the tensile property. Good tensiles were obtained in these zinc-containing welds.

It was anticipated that cadmium would violently volatilize during welding as had zinc, but this was not the case. Although weldability seems to be more improved with cadmium than with other materials tried in coating of drawn beryllium wire, the tensile strength of the welds made with cadmium-coated wire was the lowest (Table XI).

It is interesting to note that the elongations of the welds made with coated wire are all quite low compared with the 0.5% elongation for welds made with uncoated beryllium wire. Since tensile strength of unalloyed beryllium welds of 1/8-inch beryllium has been in the range of 30,000 psi, the addition of silver, tin, zinc, or cadmium to the weld metal has not resulted in a substantial increase in strength.

IV. DISCUSSION OF RESULTS

In the fusion welding of beryllium by the inert-arc welding process, proper control of the thermal equilibrium is the key to successful welding. In evaluating the heat equilibrium in welding, one needs to consider the heat input (welding amperage) and the heat output (heat conductivity from the weld area). The thicker the beryllium, the harder it is to weld, since it is more difficult to control thermal equilibrium owing to beryllium's high thermal conductivity and specific heat. Therefore, the control of the heat output in thick sections of beryllium is critical, to weld quality, and to insure weld penetration. A factor which affects the heat equilibrium and thereby the metallurgical and physical properties of the weld is the arc plasma. Since the temperature of the arc is in direct relationship with the welding amperage while other factors remain constant, an increase in welding amperage increases the temperature of the welding arc and thereby increases the temperature of the welding melt. Because increased welding temperature causes grain growth and other undesirable physical effects, it is necessary to keep the welding temperature and welding amperage as low as possible while maintaining complete penetration.

In addition to the grain growth problem, excessive amperage is the major cause of porosity and cracking. If the other heat equilibrium variables are satisfactory and if contamination is not the cause, porosity is usually the first indication that an excessive welding amperage is being used. This weld porosity is normally found on the upper surface of the bead, but porosity may occasionally be found on the bottom of the weld. The latter is usually caused by outgassing vapors from the welding fixtures, whereas porosity found in the weld metal directly adjacent to the parent metal is quite often caused by residual vaporized impurities in the beryllium. If large cracks occur in the weldment, these usually can be traced to improper thermal equilibria.

The effects of residual impurities in beryllium has long been a controversial subject, and their effects upon the fusion welding of beryllium have often been referred to. It is interesting to note that in the coated-beryllium wire studies, only those welds cracked which contained an excess of intermetallic-forming metals. The presence of silver, tin, zinc, and cadmium which do not have or do not rapidly form intermetallics with beryllium, did not cause cracking in beryllium welds. This indicates that any metal which rapidly forms intermetallics with beryllium will unduly stress the beryllium metal through volume changes and increase its tendency to crack.

Iron, which has the greatest tendency to cause cracking in beryllium welds, forms the intermetallic $FeBe_{11}$ and, to a lesser extent, $FeBe_5$.

These are generally found in beryllium-rich systems, and because they have a higher melting point than beryllium, they are present in the beryllium crystal rather than in the grain boundaries where elements, usually with lower melting points than beryllium, are found.

In $FeBe_{11}$, iron atoms react with beryllium, evolving a volume change and producing stresses on the surrounding base metal. Any intermetallics thus appear to cause distortion of the lattice of beryllium's close-packed hexagonal structure, and the amount of slip that such structure can undergo is reduced, causing premature failure of the beryllium. Not only was there fracture of iron-containing welds made in the coated-beryllium wire studies, but there were also random microcracks in one weld made with high-iron-impurity wire, in the beryllium filler wire development phase of this program. In contrast, none of the other welds in this development phase had microcracks.

This analysis in many respects, is not applicable to beryllium oxide, although beryllium oxide forms a higher melting-point compound that has a lattice structure different from that of beryllium. BeO is usually found, not in the beryllium grain, but in the beryllium grain boundary owing to the powder-metallurgy techniques used in making beryllium metal. Good, sound beryllium welds have been made in sheet stock containing up to 2% beryllium oxide and with beryllium wire of nominal 2% BeO content. Therefore, BeO, as such, is not always detrimental to the welding of beryllium. In some cases, it can be advantageous since it tends to deter grain growth.

Although major cracks have not been a serious problem in this program, microcracking is found, particularly in multiple pass welding, and has been noted infrequently in other weldments. As discussed above, residual elements that form intermetallics with beryllium increase the tendency of beryllium metal to form microcracks. Microcracks also occurred in the welds made with silicon oxide-containing beryllium wire. These microcracks were not detected by X-ray radiography as were the microcracks of the iron-containing welds. Silicon oxide causes undue stressing of the beryllium metal, whereas silicon does not, possibly because of the $SiO_2+Be \longrightarrow BeO+Si$ reaction occurring causing volume changes.

Apparently, residual elements are not the sole cause of the transverse microcracks found in beryllium weldments. It has been observed that where the arc impinges upon solid metal, the surface will

have microcracks after this impingement. Therefore, wherever possible, the arc plasma should be applied to the liquid metal only. Since the transverse microcracks found in beryllium weldments extend well into the parent metal, they are apparently caused by cracks which propagate up from a zone of the parent metal where an earlier arc had impinged upon a solid surface.

In the welding of certain heats of beryllium, stringer porosity has been observed at the edge of the weld directly adjacent to the parent metal. The indication is that this porosity is caused by one or more volatilizing residual elements trapped in the beryllium base metal. In the coated-welding wire experiments, where the volatilizing-type elements, cadmium, and zinc were plated on the beryllium welding wire, there was no weld porosity except at one area of the weld made with zinc-coated wire. The absence of porosity was probably the result of most of these elements volatilizing before the actual weld was made.

Magnesium, a volatilizing residual element found in beryllium metal, was included in the beryllium filler-wire development studies. Although excessive magnesium was not detected when the wire was analyzed, heavy porosity occurred in the weld made with this wire. This indicates that residual magnesium could be the cause of stringer porosity in welds.

V. CONCLUSIONS

1. The major factor in attaining quality fusion welds by the TIG welding process in beryllium appears to be maintaining a proper thermal equilibrium in the weld zone; the most critical variable in attaining this is amperage. It appears advisable to use as low an amperage setting as possible. The other critical aspect is that of controlling the heat flow from the weld zone such that a minimum of welding amperage can be used without other undesirable effects taking place.

2. The thicker the beryllium being welded, the more difficult the welding operation becomes, the closer the heat equilibrium for the welding operation must be controlled, and the more critical becomes the fixturing design.

3. For practical purposes, drawn-beryllium weld wire yields weld quality identical to that of hot-pressed beryllium rods, and drawn wire offers more universal uses in the future for welding beryllium. Wherever possible, drawn beryllium wire was used in this program as a standard filler wire material.

4. Owing to the lower amperage settings which are necessary in the fusion-welding of beryllium, a much lower welding speed is advisable for both manual and automatic welding of beryllium than is ordinarily used for other metals,

5. Post-heat treatment of beryllium welds is beneficial to the physical properties of the weldment. Higher temperatures (at least to 825°C) increase the mechanical properties of the weld. Post heat treatment of all beryllium fusion welds (except in the post heat treatment study has been at 825°C for 30 minutes.

6. In the welding of highly oriented beryllium sheet, the weld strength will be greater if welding is done transverse to the direction of rolling rather than longitudinally to that direction.

7. A direct current straight polarity power source can be employed instead of the standard AC equipment when automatic TIG equipment is used for making a fusion weld in beryllium, but alternating current is advised for manual TIG welding of beryllium.

8. One problem in the fillet welding studies on "T" type joints made with 1/8-inch and 1/4-inch-thick beryllium is lack of complete penetration. Although incomplete penetration on "T" type joint made by the TIG welding process is sometimes a problem with other metals, making a fillet weld with complete penetration in a "T" type joint is especially difficult with beryllium owing to its higher thermal conductivity and specific heat.

9. In fusion welds, beryllium oxide in quantities up to 2% is not harmful if it is contained generally in the grain boundaries; possibly, it is useful in maintaining small grain size in the welds.

10. Since the welds made with various additives such as magnesium, aluminum, iron, silicon-oxide, and germanium were not superior to welds made with commercially pure filler wire, it would be advantageous at this time to weld beryllium with the latter.

11. Although silicon oxide increases the tendency towards cracking, silicon does not increase the susceptibility of the beryllium metal to crack. Also, since silicon addition tends to improve beryllium weldability by improving weld metal flow, it may have possibilities for beryllium welding wire additives.

12. The additions to beryllium of substantial amounts of iron, gold, chromium, cobalt, nickel, or copper embrittles the weldment. Iron in the beryllium seems to increase weld stresses most and thereby increase the tendency to weld cracking. Copper, nickel, and cobalt have the least effect. Tin, cadmium, zinc, or silver coatings of the welding wire do not cause weld cracking. Tin and cadmium tend to increase the weldability, whereas silver coating has the opposite effect - that of making the beryllium filler wire more difficult to lay down. Welds with substantial quantities of tin, silver, cadmium, and zinc were not superior to the standard fusion welded specimen.

VI. RECOMMENDATIONS

A. Study of Additives to Improve Weld Properties

Further work of the type on two phases of the present program (filler-wire development phase and coated-wire development phase) would provide a better understanding of the effects of other elements on beryllium weldments. This type of program is effective not only for improving the weld by use of additives, but also for discovering which elements are detrimental to the beryllium weldment.

In the phase aimed at improving the beryllium weldment by the use of additives, two promising approaches have been developed in this program. One is the addition of silicon to improve the flowability of the weld metal, and the second is the coating of beryllium particles with oxide to prevent grain growth during welding. In the "coating of oxide" studies, it was proposed that 2, 3, and higher percentages of oxide be coated on the surface only of high-purity beryllium powder particles to produce welding wire. This wire would be used to maintain the fine grain size during welding. Thus far, the evidence from the program is insufficient to draw conclusions.

Further studies of the effects of residual impurities upon the weld metal should be performed. Such discoveries as the one that silicon oxide is detrimental whereas silicon is not, is of interest. Perhaps there are carbides which might be found readily in beryllium and are quite detrimental to its weld properties. More elements should be studied than were investigated in the present program.

B. Study of Heat Equilibrium to Improve Weld Properties

Because of beryllium's high specific heat, high conductivity, and high modulus, a complete study of thermal equilibrium of the weld zone may be beneficial to improve the weld properties and widen the range of applications for the fusion welding process. This thermal equilibrium study should include the heat input (from the welding arc and from external sources) as well as heat output from the weld zone. Basically the study recommended concerns methods of refining the beryllium-cast weld-metal grains by methods other than alloying. In the program just completed, we have shown that by close control of the welding variables, grain refinement could be achieved - although the grain obtained was not as fine as in the parent metals.

One method of improving the heat equilibrium would be by the development of better fixture designs and materials. Such improvement of fixturing design and materials would be especially effective in

the automatic fusion welding of beryllium. Automatic welding studies are performed in order to control more closely the welding variables so as to determine the optimum settings for fusion welding of beryllium.

Limited multiple-pass welding studies performed in this program have shown that multiple-pass welding of thick beryllium sheet would be feasible if the microcracks accompanying these welds could be eliminated. The welding of thicker materials is becoming important because beryllium aircraft structures being designed are becoming thicker. This increases the requirements for welding thicker sections of beryllium. A possible method of doing this joining of thicker sections is by metal arc-inert gas (MIG) welding, which was the subject of limited work in this program. In these preliminary studies, MIG welding of beryllium has been shown to be feasible, but considerable development work is necessary. A possibly successful MIG welding technique is that of cold-welding of beryllium by the consumable process. (This is sometimes called "Dip-Transfer" or "Short-Arc.") This process, if developed satisfactorily for beryllium, could be a high-efficiency method for depositing weld metals.

C. The Welding of Beryllium to Other Metals

It has been shown by past studies by The Brush Beryllium Company that using silver brazing alloy filler wire and simulating an aircraft structural butt joint, beryllium can be braze welded to itself, 18-8 stainless steel, molybdenum, Inconel, Monel, etc. With a beryllium to beryllium joint, in which silver-braze alloy was used, the strength at room temperature was raised to the highest yet achieved by arc-welding methods, approximately 41,000 psi. This brazing method has yielded excellent high-temperature strengths up to 1200°F. The excellent feasibility of this process has been shown, but the exact parameters of the process for joining beryllium to itself and other metals by the braze welding process are yet to be determined.

UNCLASSIFIED

THE BRUSH BERYLLIUM COMPANY, Cleveland, O. FUSION WELDING OF BERYLLIUM, by Bruce M. MacPherson and Wallace W. Beaver, April 1961. 63p. incl. figs. and tables. (Project 7351; Task 73518) (WADD TR 60-917) (Contract AF 33(616)-6413)

Unclassified report

A background section describing the accomplishments of The Brush Beryllium Company related to this fusion welding program is included. The standard conditions used for fusion welding of beryllium in this program are also given. Studies of the effects of post-heat treatment and fixturing on fusion welds are reported, along with limited studies of multiple-pass welding and fillet welding of beryllium. The effects of residual

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impurities on the weldability of beryllium are discussed in the report sections related to the beryllium filler wire development phase. Also, drawn beryllium welding wire was coated with copper, silver, gold, nickel, iron, cobalt, tin, chromium, zinc, and cadmium; the effects of these coated wires upon the fusion weld properties of beryllium are described.

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